Material flow in photovoltaics from the perspective of circular economy

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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December 2020

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Abstract

The photovoltaic (PV) sector is continuously developing, which is proven by large-scale adoption of photovoltaic modules. This trend contributes to the decarbonisation of the energy system, which is supported by a circular economy (CE) concept that aims to increase resource efficiency and reduce waste generation. Since the PV modules have a limited lifetime, the volumes of end-of-life (EoL) modules will increase in the near future. This raises concerns how to manage such a large amount of wastes, which are full of valuable materials that can be recovered and reused as secondary material. Therefore, proper management strategies should be adopted to close the loop, starting from the very beginning of the product development process. This thesis investigates the material flows within the PV industry and the recovery potential of valuable fractions through recycling, highlighting the strengths and weaknesses of the transition to a circular economy. It focuses on determining the demand for materials for the production of photovoltaic modules that should be implemented to cover the demand for solar electricity until 2100. This has resulted in the definition of bottlenecks in PV production, taking into account the availability of metals, which resources are limited.

Keywords: photovoltaics, circular economy, renewable energy, critical metals, recycling

Resumo

O setor fotovoltaico está em constante desenvolvimento, sendo essencial para a descarbonização do sistema energético. Os módulos fotovoltaicos têm uma vida útil limitada, levando ao aumento dos resíduos e deposição em aterros. Estes resíduos fotovoltaicos podem ser recuperados nos processos de reciclagem e reutilizados como material secundário criando valor. Para caminhar para economia circular importa adotar estratégias de gestão adequadas a fim de fechar o ciclo. Esta tese investiga os fluxos de materiais dentro da indústria fotovoltaica e o potencial de recuperação de materiais valiosos por meio da reciclagem, destacando os pontos fortes e fracos da transição para uma economia circular. Centra-se na determinação da procura de materiais para a produção de módulos fotovoltaicos que deverão ser implementados para cobrir a procura de energia elétrica até 2100. A análise das reservas de metais individuais, permite efetuar a determinação dos estrangulamentos na produção fotovoltaica e ano de esgotamento de materiais. Considera-se também a economia de material devido à reciclagem e o uso de materiais secundários. A revisão e as estimativas propostas podem ser úteis para pesquisas futuras, definição de estratégias e soluções a adotar.

Palavras-chave: fotovoltaico, economia circular, energia renovável, metais criticos, reciclagem

1. Introduction

1.1. Photovoltaic challenge

The growing demand for energy forces our civilization to focus interest in new energy sources. Particular attention is given to renewable energy technologies and existing energy systems, which are characterized by the fact that exploitation does not deplete its resources, or in other words, fuel. However, energy transition to renewables is associated with some changes in patterns of material use. Low-carbon energy technologies, including PV, even though they do not use primary raw materials for operation are significantly more metal intensive than conventional technologies, which mostly depend on fossil fuels (Klein et al., 2011). Therefore, the transition to a non-fossil electrical energy system would require the mining of a wide range of metals, which resources are limited.

Solar radiation stands out among renewable technologies because the amount of energy that reaches the Earth from the Sun in one day could meet the needs of our planet throughout the year, using appropriate methods of collecting and storing it (Żelazna et al., 2014).

In recent years there has been a dynamic development of photovoltaic technologies. The consequence is a price drop of this renewable technology and thus increased demand. Nevertheless, it should be remembered that a reduction in the price of energy produced in solar PV systems is possible not only by improving the production of the PV modules but also all the necessary components, that which constitute the Balance of System (BOS). The BOS cost includes items, such as the cost of the structural system the electrical system costs, and the battery or other storage system cost in the case of off-grid applications. According to IRENA thanks to BOS cost reductions the global weighted-average installed costs of utility-scale PV systems could fall by 57% between 2015 and 2025 as presented in Figure 1.1.

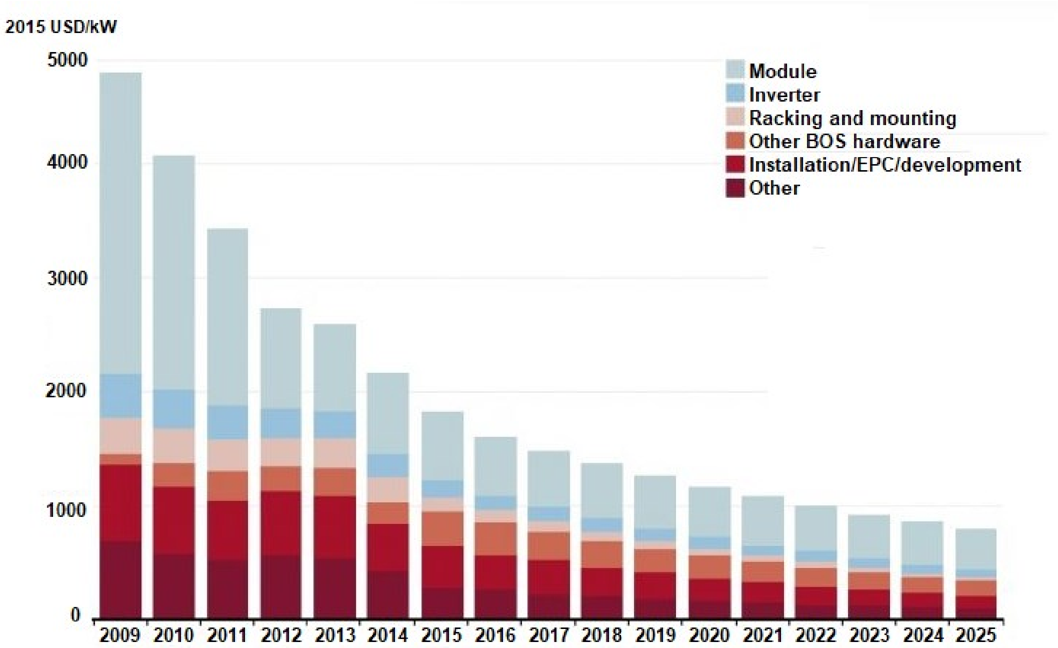


Figure 1.1. Global weighted average utility-scale solar PV total installed costs, 2009-2025 (Osborne, 2016)

Nowadays, silicon cell modules (approx. 80% of the market) dominate the market, but thin-film modules (approx. 20% of the market), in which CdTe cadmium telluride are gaining an increasingly stronger market position (Żelazna et al., 2014).

The average lifetime of solar PV panels is about 25 years (Paiano, 2015). Assuming that energy production based on this technology has become relevant since the late 90’s it can be expected that around 2050 there will be a big growth of end-of-life PV panels (Paiano, 2015). Therefore, there will be a need to implement strategies in terms of proper „waste” utilization and recycling of materials used in the production of this system. The effectiveness of these activities will determine how sustainable solar PV technology would be within its whole life cycle.

It is known that the process of recovering valuable materials used in the photovoltaic modules is necessary. In order to reduce the negative environmental impact of photovoltaic panels, proper solutions should be implemented that take into account the entire life cycle of all components of the solar PV installation. Starting from the delivery of raw materials and production stage, through service life and ends with activities related to the disposal. Recycling of waste materials is a crucial element of these strategies, because in this way it is possible to recover valuable materials and prevent the release of harmful substances such as heavy metals through inappropriate disposal practices (Padoan et al., 2019; Klugmann-Radziemska and Kuczyńska-Łażewska, 2020).

What is more, The European Union (EU) is heavily dependent on raw materials imported from other countries, which can ultimately lead to the loss of access to key materials due to various obstacles (EC, 2018). That is why it is worth considering alternative possibilities of obtaining raw materials necessary for the production of green technologies. The figure 1.2 presents the main countries from which the EU is sourcing critical raw materials, with the China as a leader.

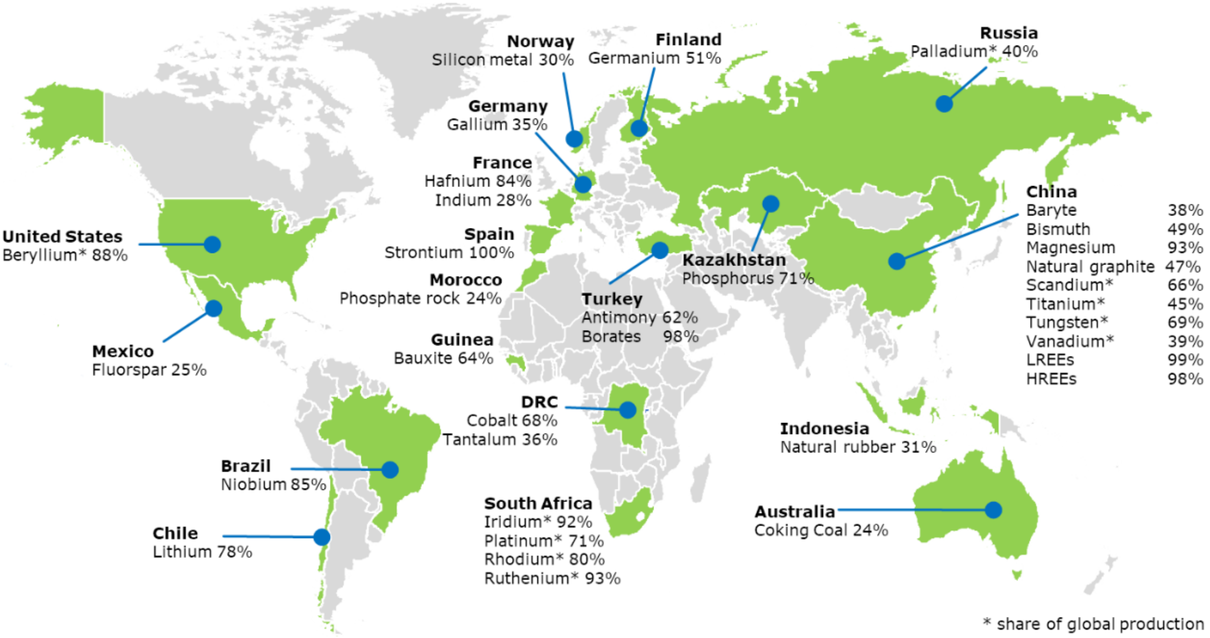


Figure 1.2. Countries accounting for largest share of EU sourcing of critical raw materials (EC, 2020a)

Here, a circular economy concept could help in the creation of secondary materials. The key problem of the thesis is to show that circular solutions may be applied in the photovoltaic industry in order to generate some materials savings. Research in this area is increasing as this is a current problem. The issue of recycling and management of photovoltaic waste becomes more and more popular and has been already discussed in the literature. Moreover, there are also articles that deal with the topic of circular practices within the PV industry. Nevertheless, there are different approaches and strategies that are very often difficult to compare. Papers on module recycling are usually divided into two groups, i.e. research on recycling methods and the environmental-economic analysis of end-of-life modules recycling.

Kim and Jeong (2016) studied different cases of manufacturer's recycling policies based on Deutsche Solar, First Solar, and PV Cycle, taking into account a circular economy concept. They described a closed-loop supply chain of PV module manufacturers with internal and external recycling systems. Experimental analysis has shown that for silicon modules, the internal module recycling system is ineffective as prices of materials are low. However, for a thin-film module manufacturer (CdTe), it is more profitable to recycle PV modules within the own system than using the external recycling facility due to the high value of the materials. Wu et al. (2019) investigated three recycling models in terms of Extended Producer Responsibility (EPR) from the reverse supply chain point of view, which is also a part of the circular economy model. They analysed the influence of government subsidy and the level of Producer's recycling responsibility on the recycling profit. Another study carried out by Herceg et al. (2020) explored different end-of-life approaches for the main photovoltaic technologies available on the market. The work confirmed that via recycling, it is possible to enhance the environmental profile of PV electricity. However, some improvements in recycling solutions are required in order to make a photovoltaic technology a leader in the energy transition. Circular economy practices in the management of end-of-life PV modules are also described by Sica et al. (2018). This work shows that the implementation of the closed loop practices requires appropriate adjustments in the whole value chains. Starting from the production up to disposal. What is more, thinking of waste as a product will require the development of new business models and change of consumer behaviour. The possibilities of introducing a circular economy into the PV industry were also examined by Farrell et al. (2020). They found that the sustainability of module recycling can be ensured by lowering the costs associated with this process as a whole, which can be achieved by optimization of the PV modules collection as well as the recovery of individual fractions. In order to achieve closed-loop of materials used in the photovoltaic industry, it will be necessary to design out waste and implement good eco-design strategy. That has been confirmed by Ratner et al. (2020). Recycling processes, which are divided into chemical and physical, have been described in the literature, among others by Azeumo et al. (2019). Maani et al. (2020) also studied recycling methods for c -Si and CdTe PV wastes as well as recovery possibilities. They stated that thermal methods are more eco-friendly than chemical and mechanical ones. Moreover, recovery of individual metals should be prioritized due to the impacts and costs. It is known that government plays an important role in the transition to a circular economy within PV industry, because it may increase the R&D projects and create favourable conditions that accelerate and support the development of recycling technologies. This is emphasized in the paper prepared by Kim and Park

(2018). It is also recommended to control and monitor waste flows at the national level, which will be crucial for the design and planning of PV waste management system. Chowdhurya et al. (2020) explored the current status of solar PV panel waste recycling in terms of technology, environmental protection, recycling policies and economic features. They recommended future improvements in technology and policymaking that could be implemented before the largest wave of photovoltaic waste, which would accelerate R&D in PV module recycling. The directions of R&D for c-Si modules recycling was developed by Heath et al. (2020). It should focus on the reduction of prices related to recycling, a sustainable, circular supply of materials and the reduction of environmental impacts.

1.2. Goal and scope

The growth of photovoltaic installations in recent years positively contributes to the energy transition. This work aims to explore the possibilities of implementing the concept of a circular economy for solar PV technologies, which is primarily based on increasing the efficiency of using raw, usually critical materials and waste reduction. Solutions promoted by the circular economy include recycling of end-of-life modules and the use of secondary materials.

However, the circular economy in terms of photovoltaic industry or any other industry is not only about end-of-life modules and waste management. The circular economy concept gives a lot of opportunities for government, industry, businesses as well as for consumers to rethink the traditional model of consumption and change business models in order to obtain better economic, environmental and social outcomes (Smol et al., 2019). Circular economy assumes collaboration between stakeholders in terms of standardisation, coordination and searching for the new business models and sustainable solution.

The transformation to the closed-loop economy should be supported by play policymakers, who are responsible for the implementation of supportive regulations and the creation of a friendly environment for circular business models. Standardisation of waste and recycling legislation could unlock more efficient solar PV recovery and recycling.

One of the most important tasks is to establish an Extended Producer Responsibility scheme (Gentilini and Salt, 2020) and support partnerships through the whole value chain between players, especially between public-private representatives. It is very important to designate the entity responsible for PV wastes which will take care of their appropriate management. It should be a collaborative process that engages the entire industry.

What is more, according to CE it is necessary to define the standards of PV module design and data management processes, such as labelling and materials passports, that may enable much easier and effective processing and disassembly of PV modules.

The goal of this work is to promote circular practices in the PV industry, which are based on material flows. That is why, it starts with an analysis of the present and future demand for raw materials for the production of photovoltaic technologies based on different scenarios taking into account policies and requirements in terms of the energy transition, supported by a circular economy. Availability of resources and critical materials are considered. Due to the latest trends, decarbonisation and energy transition, the share of renewable sources in the energy mix will increase. This implies a huge increase in demand for raw materials crucial for the production of such technologies. For some of them, it is already a big issue, because the availability of some components may be insufficient to cover the demand.

Therefore, it is very important to estimate such material consumption in order to supports policymakers, which are responsible for providing a sustainable and secure supply of these materials and industries which base their entire operation on the access to raw materials (Carrara et al., 2020).

1.3. Methodology

According to European Commission (EC) circular economy outlines that „the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimised" (COM no. 614, 2015). Therefore, it is important to understand an economy's societal metabolism. It means to define and quantify the materials flowing within the economy and precise how they are used in society and their level of circularity.

Such an approach may be also adapted to a single process or technology, as in this case for the photovoltaic industry. That is why a material requirement was calculated. Material flow analysis (MFA) has become one of the basic tools in industrial ecology and may be applied in waste management and planning recycling strategy. It is a useful analytical tool for determining flows of materials defined on a spatial and temporal scale which has been widely used as an environmental tool for waste and resources management (Bringezu, 2006; Brunner and Rechberger, 2004). It is based on the principle that "materials cannot be lost" which corresponds to the first law of thermodynamics implying conservation of mass and energy by drawing a system boundary within time and space. It was implemented in this work, which was preceded by a literature review on implementation of circular solutions in the photovoltaic industry, new technological solutions for photovoltaic modules. Reports on the photovoltaic markets and prospects for its development as well as the most important challenges were also analysed.

MFA is made up of a standardised methodology and tools adopted by Eurostat in 2001 and mainly used at a macro and mezo level to promote sustainability, resource efficiency and performance improvement. It is applied during decision-making process related to legislation and policy (Bringezu, 2006), practice (Brunner and Rechberger, 2004), the development of the CE (Milette et al., 2019) or decoupling (UNEP, 2011). It is usually combined with Life Cycle Assessment (LCA), it helps to model, assess and quantify the impacts of waste flows. In addition, MFA Sankey diagram, which is a visualisation technique for displaying flows, confirmed its effectiveness in public communications, which is very important assuming that CE strategies involve many stakeholders (Tanzer and Rechberger, 2019).

When it comes to waste and resource management, it is important to know and understand the flow of materials in the system, which will give a better picture of the problem and also is extraordinarily helpful in the preparation of appropriate strategies. Therefore, via MFA it is possible to evaluate the proposed solution in terms of the effectiveness of solving a problem, as well as achieving the assumed goals related to waste utilisation and material recovery. Using MFA, material flows were developed, showing a quantity of end-of-life modules produced as well as material requirements for new devices that would have to be manufactured in order to cover the electricity demand.

In this paper, MFA has been proposed for the assessment of recycling processes in photovoltaics that minimise the environmental impact of the waste generated by this technology and material consumption. Such methodology allowed for the identification and determination of the quantity of material requirements.

In the first step of the material analysis, the power demand until 2100 was outlined, taking into account the energy demand forecasts presented by IRENA (IRENA, 2020) in the Transforming Energy scenario until 2050, and the one RCP2.6 scenario for 2050-2100 (Vuuren, 2011). Subsequently, data on panels from different PV manufacturers websites and data sheets were collected in order to calculate the average material intensity for three technologies, i.e. crystalline silicon module, CIGS and CdTe panels, which stands for the majority of technologies available on the market. In the next step, the material requirement overtime was calculated, which was referred to the reserves of individual metals, resulted in the calculation of the depletion year, i.e. until when, taking into account the assumptions that had been made, each metal will be available.

The purpose of such procedure was to illustrate the problem of depleting metals and to emphasize the importance of access to raw materials in the production of „green” energy. The final task was to find an indicator that will monitor the level of consumption of primary materials. Undoubtedly, such a parameter is needed, because secure supplies of raw materials are essential not only in the photovoltaic industry, but in any other industry or the whole economy. However, assessment of depletion phenomena is very problematic, because it can never be completely verified empirically. However, abiotic depletion parameter has been selected. Using SimaPro software abiotic depletion potential for each of the metals in the PV module was calculated and then the values were converted for one module. Obtained results may be helpful in making optimal decisions or verifying which process could be modified to gain maximal environmental benefits with reference to the availability of resources.

1.4. Thesis structure

Photovoltaic modules generate „green energy" using renewable, unpaid fuel that does not cause pollution to the atmosphere, which is solar energy. However, taking into account the entire lifetime of the panels, i.e. from production to disposal, significant amounts of non-renewable resources are used, and energy is consumed. As a result of these activities, pollutants and waste are generated at each stage, which affects the environment.

In this work, the material analysis was carried out based on most popular types of photovoltaic modules, which is necessary for the development of appropriate strategies for waste management and sustainable resource management. It is focused on the main possibilities of adapting of the circular economy concept in the photovoltaic industry with an emphasis on the end-of-life stage.

The first chapter defines the thesis problem, methodology and the purpose of the work. The second chapter is an overview of the photovoltaic market, along with the development prospects. The most important technologies available on the market were presented and the concept of the circular economy was defined. The main materials used for the production of photovoltaics were characterized, and strategic metals and challenges that are associated with the photovoltaic industry in terms of ensuring access to the necessary metals were investigated. The third section deals with the management of end-of-life modules and the possibility of their recovery and recycling, i.e. activities that are proposed by the circular economy.

The last chapter is a material requirement analysis. It aims to determine the capacity growth rates and material flows required to cover the energy demand from photovoltaics. In the first step simulation of energy demand from photovoltaics was investigated as well as the power requirement from photovoltaic modules up to 2100. Then, on the basis of available technologies on the market, the material intensity was calculated, which was followed by the material flows over time by individual fractions, taking into account the module lifetime and the share of different technology choices. The bottlenecks and strategic metals in the production of solar PV modules have been defined. The year in which the reserves of individual metals intended for the production of photovoltaic cells runs out were calculated. Subsequently, the possibilities of recovering valuable metals in the recycling process and the impact of recycling on demand for primary metals were also analysed. In the last point, the abiotic depletion index was calculated, which can be a parameter used to monitor the level of metal consumption in the production of photovoltaic panels.

This analysis helped to assess the effectiveness of 'closing the loop' and thus answered the question of how much we can rely on the circular economy in relation to the PV sector.

2. State of knowledge

2.1. Circular economy

Our entire economy and its development are dependent on resources such as land, water, materials and energy (EEA, 2014). What is more, consumption of resources is responsible of many environmental problems such as pollution, climate change and extinction. Even renewable technologies known as ”green” need to have raw materials, land or solar exposure and cannot grow indefinitely, because the reserves are limited (Giurco et al., 2019). Therefore, is it possible to constantly develop and increase gross domestic product (GDP) if the planet and its regenerative abilities may be not enough?

Many economists and policymakers point to a new concept, which assumes that economic growth and welfare may be “decupled” from environmental pressures and impact (CRAIG, 2015; COM 2014). For example, the Nordic countries have implemented the “Circular Public Procurement in the Nordic Countries”(CIPRON), which is a process aiming to provide conditions and criteria that would stimulate energy and material savings and closed material loops, in addition to spreading innovative solutions and creating markets for clean solutions (Busu, 2019). Therefore, the economy can develop and grow without negative influence on the environment and additional resource usage, which cause many environmental problems (Ward et al., 2017). Decoupling concept is presented in figure 2.1.

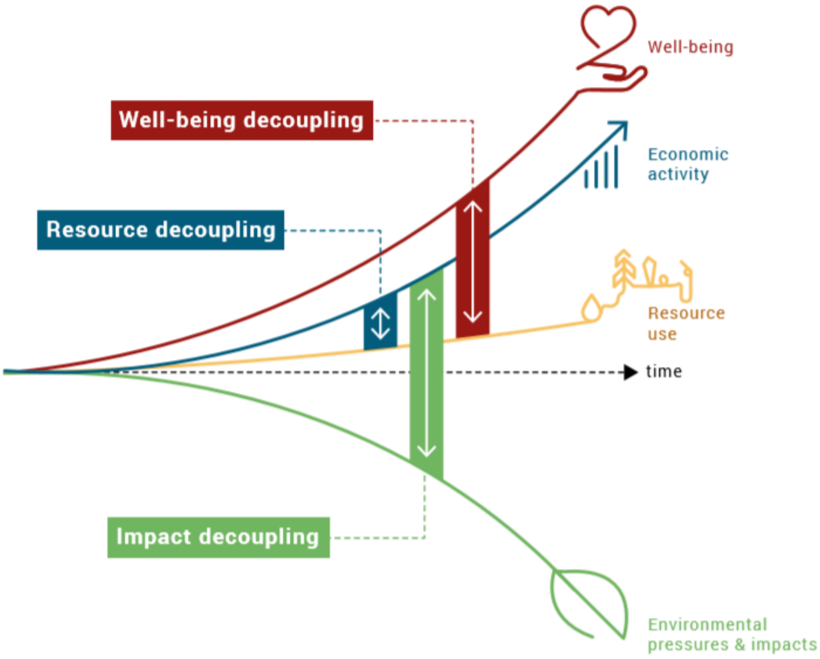


Figure 2.1. Decoupling concept (IRP, 2019)

Since global resources are limited, such concept may be crucial and allow the economy and GDP and meet environmental commitments. These assumptions are implemented by the circular economy. According to Ellen MacArthur Foundation “The circular economy provides multiple value creation mechanisms that are decoupled from the consumption of finite resources” (EllenMacArthur, 2015a).

For years, the economy systems have been based on linear models, which runs on principle “take, make, dispose”. In such a model, raw materials are extracted and then processed into products and goods. In the next stage, these products are consumed, and when they lose their usefulness are removed as waste back to the environment. During this process, because of inefficiency and waste value is lost. (EllenMacArthur, 2015a).

What is more, the European Commission has adopted a new Circular Economy Action Plan - one of the main blocks of the European Green Deal, Europe’s new agenda for sustainable growth. It announces initiatives for the whole life cycle of products, targeting for example their design, promoting circular economy processes, fostering sustainable consumption, and aiming to ensure that the resources used are kept in the EU economy for as long as possible (COM, 2020).

Linear economic model, which is based on large amounts of easily accessible, cheap raw materials and energy has contributed to the industrial development. However, due to the increase in raw material prices, their availability and volatility, which has on impact on secure supplies policymakers and business leaders change the mindset. They began to look more closely at the circular economy and the benefits it can provide. They have noticed that despite significant progress in improving resource efficiency, any system based on consumption rather than restoring resource use causes significant losses throughout the entire value chain. Therefore, a new economy model has gained in importance, which redefines „take-make-dispose” model taking into account positive society-wide benefits. Figure 2.2 presents linear and circular economy concept.

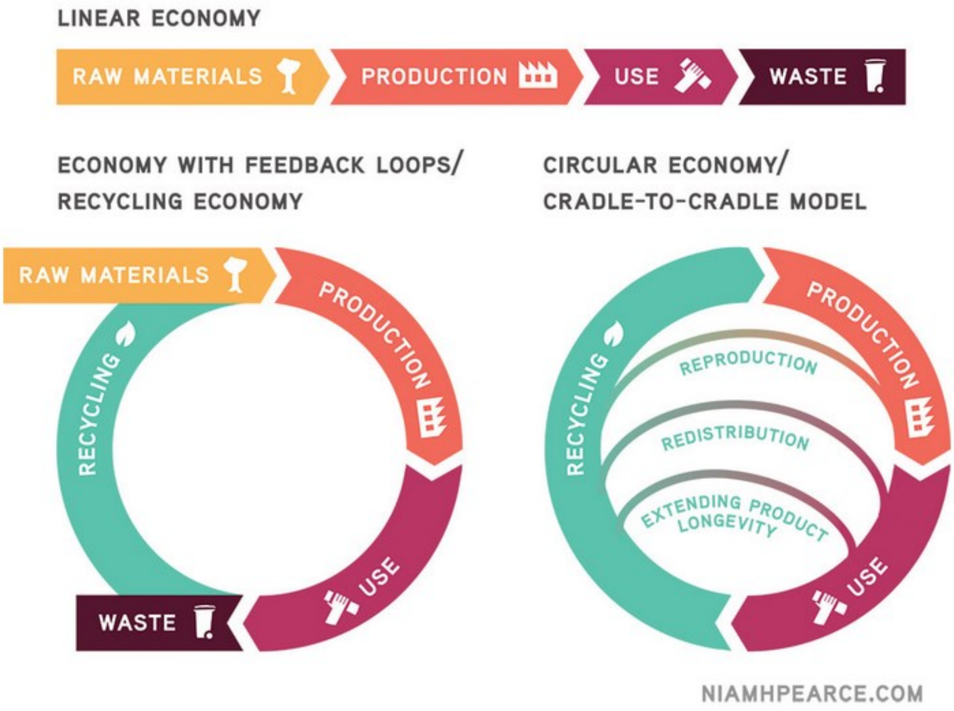


Figure 2.2. Linear to circular economy concept (Pearce, 2017)

More than 200 definitions of the circular economy already exist in the scientific literature (Kulczycka, 2019). However, the most commonly used definitions are prepared by the Ellen MacArthur Foundation which say: „A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It replaces the „end-of-life" concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (Ellen MacArthur Foundation, 2015).

In practice, such a model reduces waste to a minimum. A product that has reached the end of life and its materials are kept within the economy wherever and as long as possible. This means that these materials can be efficiently used many times, and thus create further value.

2.2. Photovoltaics

In order to produce electricity from solar energy a series of interconnected elements are needed, which form a PV system. Such a system consists of two types of components, regardless of the size of the installation or its application (Hernández-Callejo et al., 2019). One of them is solar PV module and the other is balance of system technologies (BoS). The main element are the photovoltaic cells, which use the photoelectric phenomenon to produce electricity. Whereas, the BOS system is responsible for the proper functioning of the entire photovoltaic installation and adjustment of the output, which then goes into the electricity grid or may be stored in a battery or other energy storage technologies. They have a significant share in the whole PV installation costs (Baumgartner, 2017). The BoS system can be divided into three groups of components: mechanical, electrical and electronics. They include, among others, converters, trackers, solar irradiations sensors, electrical switches, wires, cables, electronics for energy management, protection devices, mounting system, batteries, which are adjusted to the needs of a specific project (Kaushika et al., 2018). Figure 2.3 presents a typical PV system components.

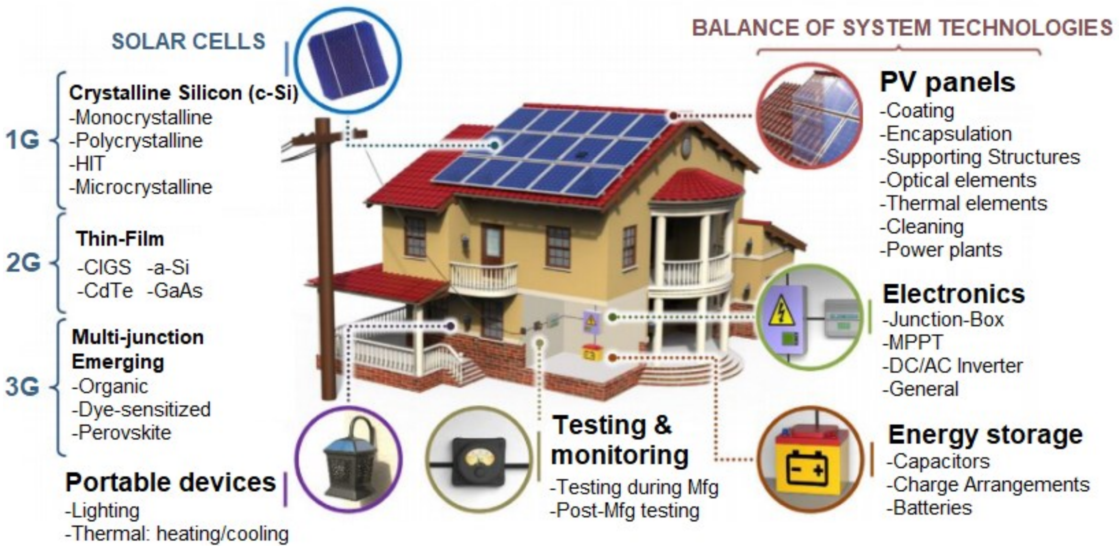


Figure 2.3. PV system (Shubbak, 2019)

Such a PV installation may be used to produce electricity on a big scale, but it can also create smaller configurations that serve for personal use in mini-grids. It is a great solution to bring energy to hard-to-reach or remote places, which are deprived of access to the grid and transmission lines.

Photovoltaic technology is considered as clean and environmentally friendly source of energy, since it generates small amounts of waste during its operation. Therefore, it may play an important role in transition towards circular economy. However, to get the full picture of solar PV technology and its impact on the environment it is important to take into account the whole life cycle (Figure 2.4). First of all, we should not ignore the production stage which involves consumption of raw materials. According to Global Resources Outlook 2019 prepared by UN (IRP, 2019) extraction and processing of natural resources is responsible of 50% of the total greenhouse gas (GHG) emissions. What is more, the end of life stage, involving disposal and recycling may be associated with the generation of some waste, pollution and loss of energy and labour.

Figure 2.4. Life cycle of the PV module (Śliwińska et al., 2009)

It is important to start introducing circular economy practices at the very beginning (i.e. design and manufacturing stage) of each generation of PV modules and consider how the waste can be designed first and secondly if they have been produced for maximum reparability, recyclability and reusability.

The circular economy works towards a reduction of waste, but also towards the generation of new markets, increasing utilisation rates, resource efficiencies, economic stimulation and better social outcomes. It allows for better control of resource streams and introduction of innovation through the supply chain. Due to the closing of the loop, it is possible to enhance the collaboration within the supply chain and create services that capture the value of PV modules and PV waste in every stage of the lifecycle of such technology.

Moreover, these benefits may be maximised when all the elements of a business model are circular. The model that is based on sustainable material development, sharing and reusing platforms is much more sustainable than one that focuses only on recycling. It is about reducing total material demand in every stage of creation process, increasing overall efficiency and not only dealing with wastes.

Therefore, to get the best benefits from the circular economy, three elements need to be brought together: circular design, circular use and circular recovery.

Circular design can reduce effort and generation of wastes in further steps of a lifecycle. What is more, it helps to decrease material, finance and energy consumption and may lower the emissions to the environment. The design of PV modules should aim for an extension of the lifetime of PV cells by increasing durability and utilisation rates, which will reduce the need for primary materials in the future. It is also important for designers to rethink how materials are purchased and if they are acquired in a sustainable way. The design should also take into account future disassembly and thus ensure a more efficient deconstruction phase by appropriate design, which may be useful for further processing of the EoL modules.

Circular use supports new business models, based on sharing, services and digital platforms. In this way, renewable and affordable energy may be more accessible.

Circular recovery allows to create value from waste and enable new revenue to be generated. Moreover, recovery, reuse and recycling processes have a high potential for job creation as well as new, dedicated infrastructure and facilities.

By introducing these principles and stimulating leadership and collaboration, the inevitable transition to a circular economy can be smooth. Such a transition can bring many benefits.

2.2.3. Construction of a solar PV module

The basic element of a photovoltaic system is a photovoltaic cell. When exposed to sunlight, it becomes a source of direct voltage. The cells are grouped and combined in order to form a photovoltaic module, which forms a photovoltaic panel. The set of panels forms a photovoltaic system, also called a PV generator or module field. Thus, a single cell (Figure 2.5) is the foundation of any PV system and its energy yield depends on its performance (Klugmann-Radziemska, 2014).

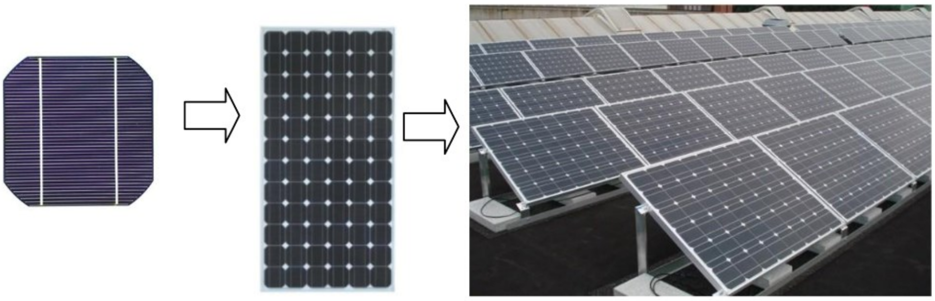


Figure 2.5. Photovoltaic cell - PV module - PV system (Klugmann-Radziemska, 2014)

The typical module with all structural elements is presented in figure 2.6. It is composed of the following layers: a tempered glass layer, two sheets of ethylene vinyl acetate (EVA) that surround the semiconductor, which may vary depending on the panel type, then plastic backing (or back-sheet). It is the white surface with the composition of Tedlar (polyvinyl fluoride) and polyethylene terephthalate. The aluminium frame protects all sandwiched layers to which the junction box is attached. Sometimes an additional anti-reflective coating is added over the glass surface (Padoan et al., 2019).

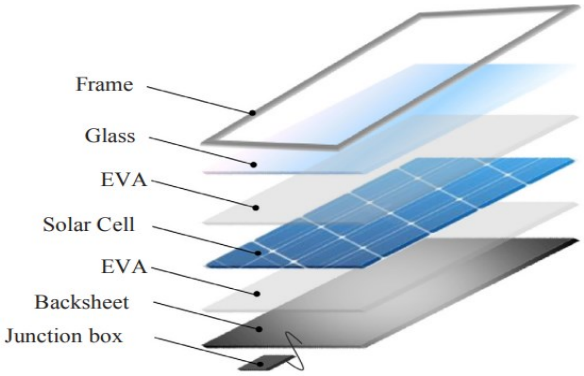


Figure 2.6. General structure of a PV panel (Padoan et al., 2019)

Silicon is the most commonly used as a semiconductor material for the production of photovoltaic cells, both in mono or polycrystalline form. If we consider the weight of the panel, 76% stands for the glass (panel surface), 10% is polymer (encapsulant and backsheet foil), 8% aluminium, which is found mostly in the frame and only 5% is silicon (PV cells), the other elements are copper in interconnectors (1%) silver (0.1%) and small amounts of other metals like tin and lead.

Of course, different materials are used depending on the panel type. There are also differences in the energy demand for the production of 1m^2 of solar PV panel. However, for mono- and polycrystalline silicon panels, these differences are very small. Monocrystalline silicon cells are easier to recycle (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020).

2.2.4. Types of solar PV technologies

Classification by generation is the most common division of the photovoltaic modules, which distinguish first, second and third generation. Figure 2.7 presents the division of photovoltaic panels taking into account generations (Sampaio et al., 2018).

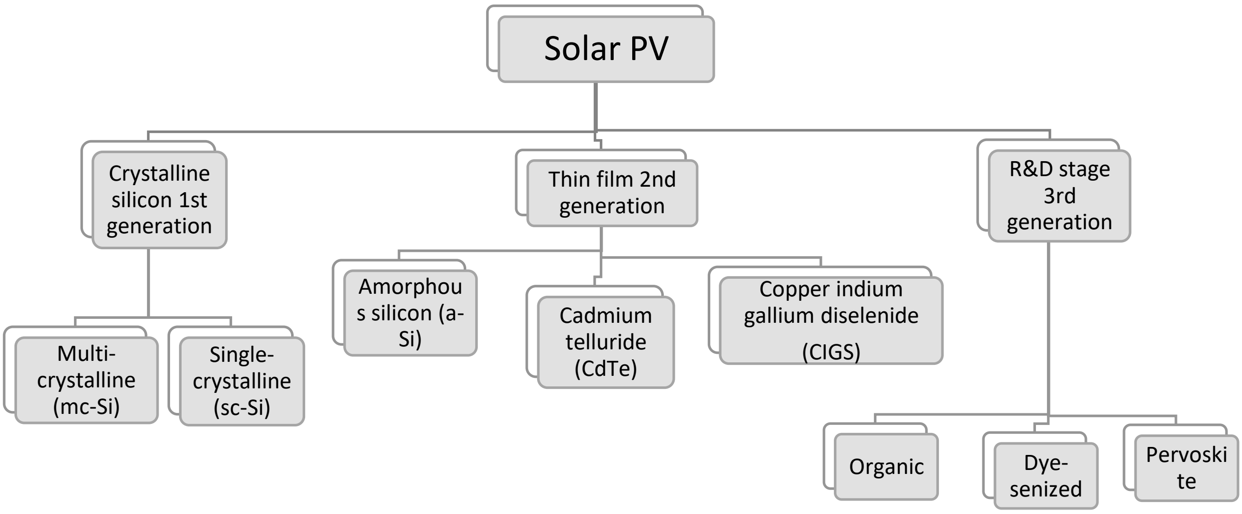


Figure 2.7. Schematic diagram of different solar photovoltaic (PV) technologies (Månberger and Stenqvist, 2018)

The first generation is crystalline silicon technologies (polycrystalline and monocrystalline) that are already fully commercialized and have dominated the market. The second generation stands for thin-film cells and it has been one of the most dynamically developing area of the solar PV technology in the recent years. The semiconductor in a form of amorphous silicon (a-Si), CIGS (copper indium gallium selenide) and cadmium telluride (CdTe) is applied as a thin layer. The third-generation cells are intended to "imitate the nature". They include organic photovoltaic cell technologies, which are still under development, but seems to be an interesting alternative because of the low price (Sampaio at al., 2018). All three groups are described in more detail below. The following sections explore each generation of PV modules.

- **First generation**

The first-generation PV panels are those in which silicon acts as a semiconductor. Cells in the form of wafers of approximately 2 mm thickness are made of mono- or polycrystalline silicon. The main representatives of this group- monocrystalline and polycrystalline silicon panels have the largest market share (IRENA, 2016). Monocrystalline panels are manufactured using the Czochralski method, which ensures a high level of purity (Bagnall et al., 2008). This makes monocrystalline panels more expensive, but also more efficient (13–19%). Monocrystalline panels are made of silicon, which has a homogenous structure, and the crystal lattice is continuous in the whole structure. Therefore, there is no grain boundaries. They are dark blue and black. Modules consisting of monocrystalline cells are very efficient. However, the ratio of their power drop with the temperature increase is the highest among all solar PV modules. It is also the most expensive solution among silicon-based modules.

The polycrystalline modules are made of crystallized silicon, which has a partially ordered structure, which corresponds to reduced efficiency and lower performance They usually have a characteristic blue colour with clearly defined silicon crystals. It is characterized by efficiency in the range of 14-18% and a moderate price. Modules from polycrystalline cells are highly efficient and in recent years are beginning to "catch up" in this respect monocrystalline. Still high, but lower than in the case of mono modules is the indicator of power decrease with increasing temperature. It is the most widespread technology, although it has less efficiency than the monocrystalline one, but its production process is cheaper.

Undoubted advantages of wafer-based c-Si cells are their stability and reliability. They can operate under outdoor conditions that do not affect their performance. Unfortunately, the production process of silicon panels is very expensive, because of its complexity and large amounts of highly purified silicon required (1 MWp consumes about 15 t of feedstock) (Dong et al., 2011).

At first, for the production of PV modules scrap from the microelectronics industry was mainly used, so the price of the raw material was low. With the development of solar PV industry, the demand for silicon increased, which influenced the appearance of silicon production plants. The process of cutting wafers from the crystal with a wire saw generates large amounts of waste and can cause damage of the cells or lead to the destruction of silicon wafers, what affects also the technology price.

- **Second generation**

The advantage of the second-generation technology is a significant reduction in the consumption of expensive materials for the production process with comparison to the crystalline silicon panels, thereby improving the price/power ratio of the cell. After years of research and technology development, thin-film solar cell production is becoming increasingly widespread. Such cells consist of thin layers (with the thickness of 1–10 µm) of semiconductor deposited on a cheap and solid backing as glass, polymer or metal. Therefore, to convert the same amount of solar radiation thin-film cells need smaller amount of semiconductor material. What is more, their light construction, pleasant dark colour, and elastic properties make them more durable, aesthetically and able to take any shape. They may be used as building components (BIPV- PV installations integrated with the building) (Almosni et al., 2018).

The efficiency reaches about 15% up to 22% (Dimmler, 2014), which is the result compared to even polycrystalline panels, which are the most popular on the market.

Thin-film panels commercially available at the moment are made of (fotowoltaikaonline.pl):

- cadmium telluride (CdTe cells). It is the most widely known technology covering about 50% of the thin-film market. However, cadmium telluride contains significant amounts of cadmium, which is toxic and there is a risk of tellurium shortage.
- amorphous silicon (a-Si cells). This technology is most similar to standard silicon panels. It is definitely less efficient, so it is usually used at low loads in applications such as consumer electronics.
- combinations of copper, indium, gallium and selenium (CIGS panels - Copper Indium Gallium Selenide) their efficiency ranges from 12-14%.
- gallium arsenide (GaAs cells). It is a very expensive technology used primarily in spaceships. It is intended for large photovoltaic installations operating in unusual conditions.

- **Third generation**

The latest third generation includes technologies that have just gained commercial status or are still in the development stage. Such technologies are concentrator photovoltaics, dye-sensitized solar PV cells, organic cells, and hybrid cells. CPV technology uses concentration of sunlight through special lenses or curved mirrors combined with traditional solar modules (Sampaio et al., 2018). To enhance the effect a system of trackers is implemented to follow the position of the sun and gain as much solar radiation as possible. The efficiency is very high, at the range of up to 25% as well as the cost. The dye sensitized solar cell (DSSC) imitates photosynthesis. The main component of such cell is the semiconductive layer of TiO_2 nanoparticles with the dye adsorbed on it, which is responsible for the absorption of solar radiation. The dye sensitizes a nanocrystalline TiO_2 because it increases the extent of solar radiation absorption by the illuminated electrode. The organic cells are made of biodegradable materials such as organic polymers or small organic molecules. They are cheap because they need small amounts of materials and are processed in low temperature. However, their efficiency is only 5% and may degrade. Hybrid panels combine various current technologies, both organic and inorganic semiconductors.

There is also another innovative technology called passivated emitter and rear cell (PERC). In such system an additional dielectric passivation layer is added on the back side of the cell. This solution makes the light of longer wavelength, i.e. the one that reaches the panel in the morning and evening, which has not been fully absorbed by the silicon, that can be reflected and redirected back to the silicon wafer and successfully converted into electricity. It increases the efficiency of the solar PV panel, because more light is absorber (Paiano et al., 2015).

2.3. Market overlook

World energy production has changed over the years in terms of both quantity and source - in the long run. Figure 2.8 shows how global energy consumption changed in the years 1971 to 2020. It is visible that in recent years there has been a significant increase in the production of energy from wind and solar PV.

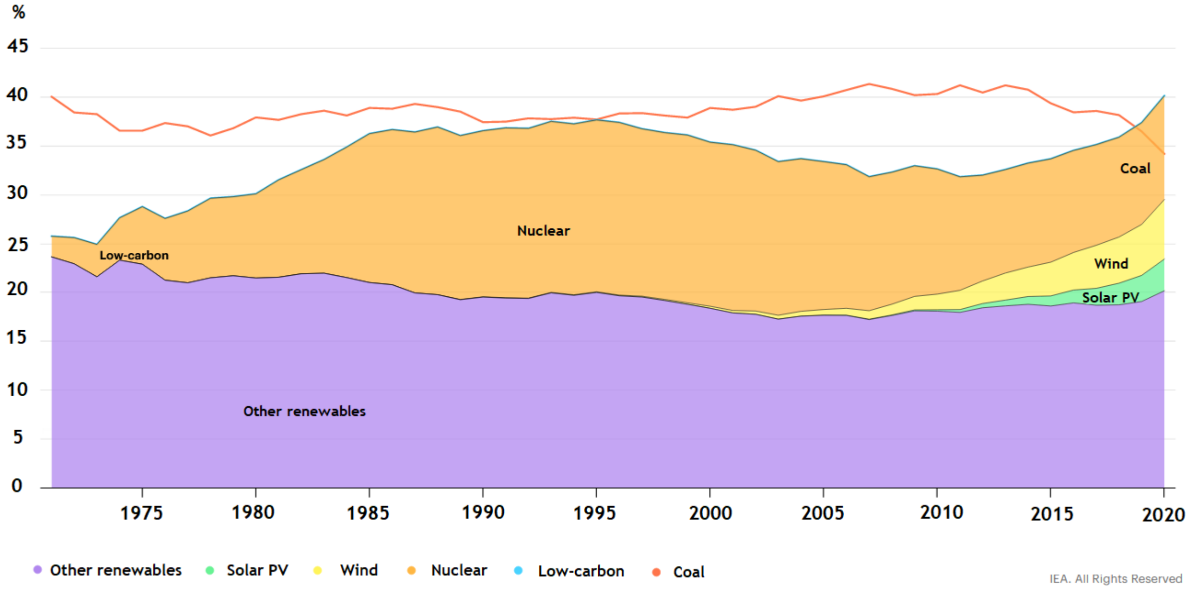


Figure 2.8. Global generation shares from coal and low-carbon sources, 1971-2020 (IEA, 2020b)

Currently, the energy sector is changing and striving for decarbonisation. In this connection it enhances the implementation of technologies that are based on renewables sources which will contribute to build a sustainable future.

Among the new technologies on the generation capacity market, renewable technologies play the most important role, including systems based on solar and wind energy, which are becoming an increasingly cheaper source of electricity on many markets. Furthermore, renewable energy production is now growing faster than the overall energy demand. It is estimated that the vast majority of renewable energy sources will be fully cost competitive over the next decade (IRENA, 2020). Therefore, the energy transformation has already begun, and the energy market can change a lot in the near future.

Figure 2.9 shows the development of energy from renewable sources, considering power generation and addition of capacity. The largest increase in power capacity can be observed among wind and solar energy technologies.

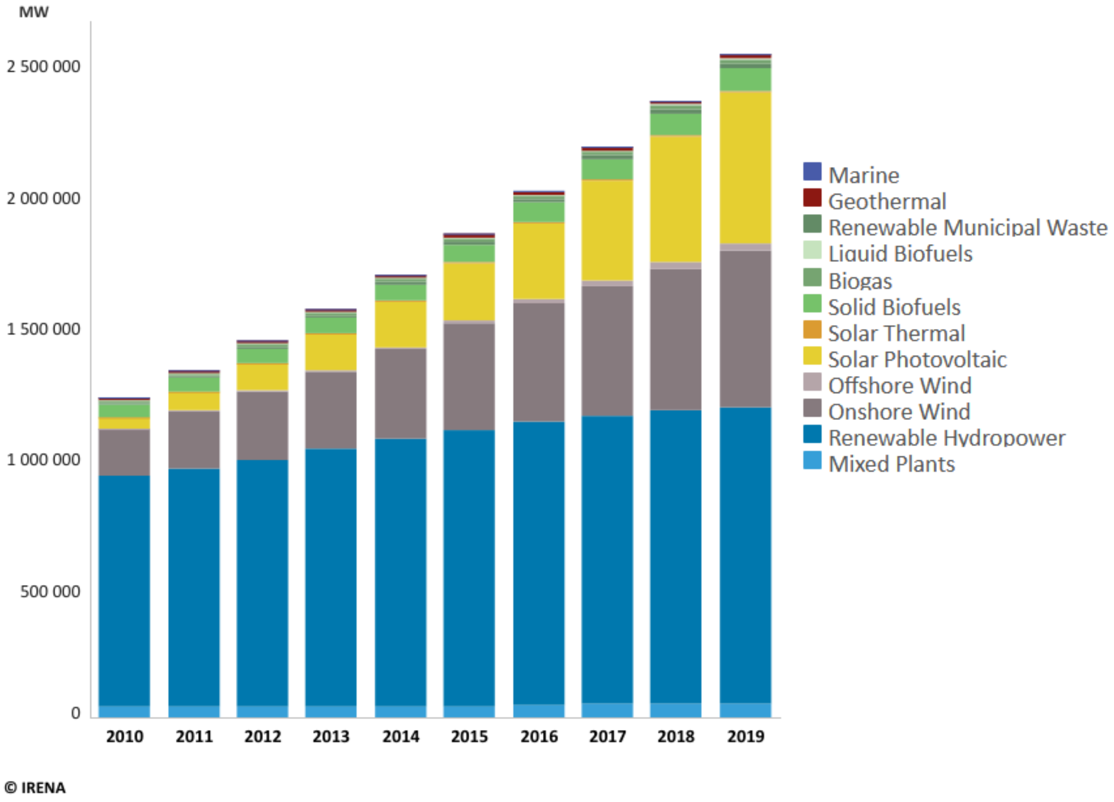


Figure 2.9. Global cumulative power capacity of renewables (IRENA, 2018)

According to IEA (IEA, 2020c), in order to carry out the energy transformation a continuous development of renewable energy technologies will be necessary or even its acceleration. Solar energy along with the wind energy, would lead the way for the transformation of the global electricity sector, what is visible in figure 2.10, taking into account STEPS and SDS scenario.

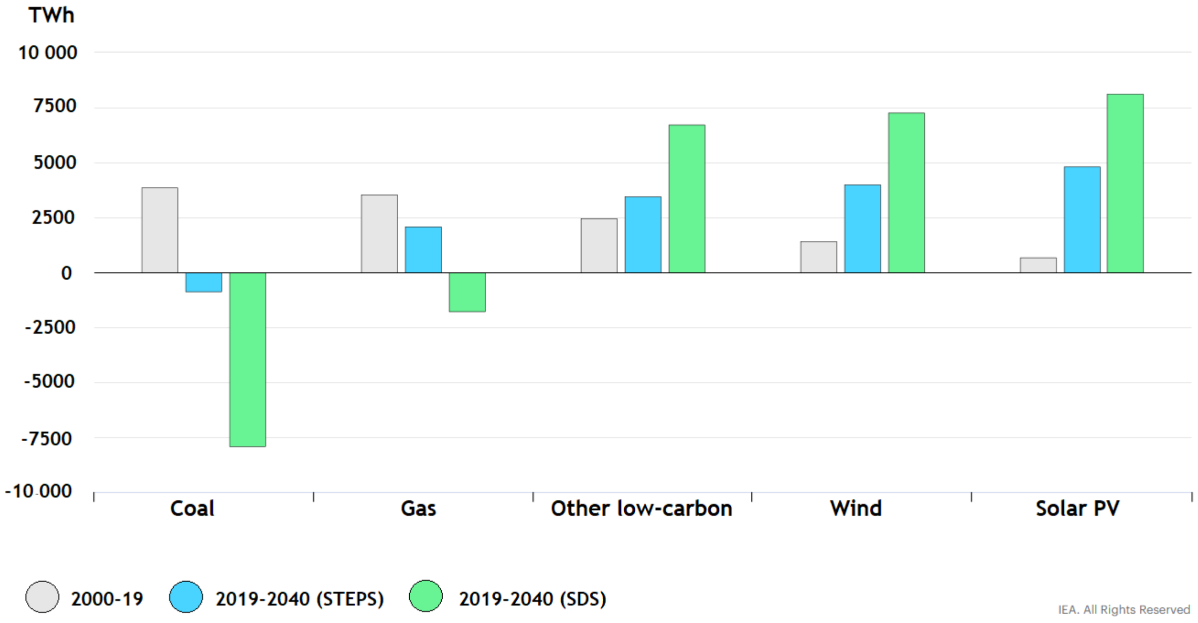


Figure 2.10. The rising importance of electricity derived from renewable energy (IRENA, 2018)

The graphs presented in figure 2.11 and figure 2.12 show the development of solar PV farm over the years in the form of new installed capacities per year and future projections. It can be seen that the installed capacity in PV installations has been gradually capacity increasing, with a small decrease in 2012 and 2014. In 2018 another new 95 GW were deployed and in in 2019, the capacity installed in solar farms reached the level of 580 GW (figure 2.11). Such a development of photovoltaic is a consequence of a significant cost reductions and the introduction of new regulations and supportive policies regarding this technology as well as research and funding.

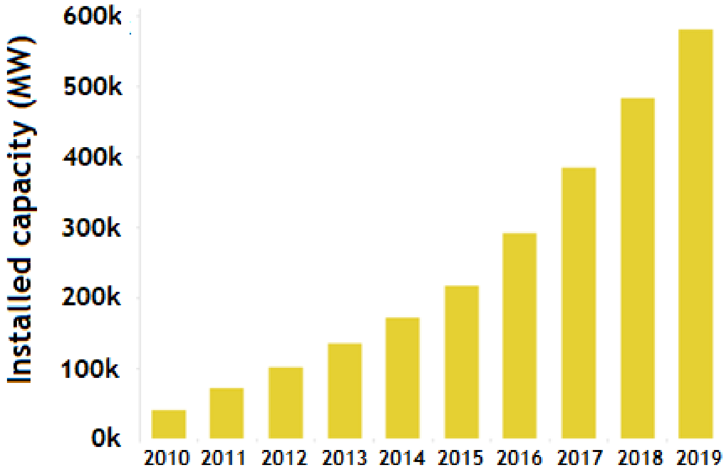


Figure 2.11. Installed capacity trends in solar photovoltaic (IRENA,2020a)

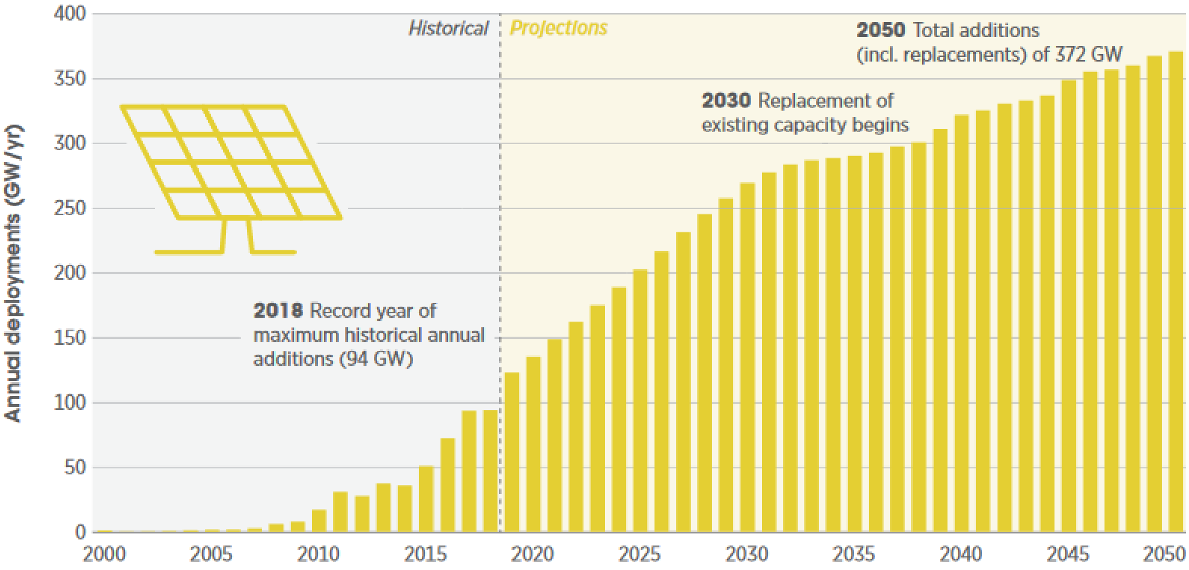


Figure 2.12. Annual global solar PV additions according to REmap scenario (IRENA, 2019)

If this trend continues, it is anticipated that PV market will grow in the next three decades according to IRENA. Apart from the improvements related with the modules' efficiency the replacement of end-of-life panels with new ones based on newer technological solutions will also have a great impact on the results. According to estimates, in 2030 the power addition would reach 270 GW and 372 GW in 2050, which is 4 times more than in 2018.

Global solar PV market in recent years has been dominated by Asia, which stands for over half of the solar PV power capacity (figure 2.13) *(*Detollenaere et al., 2020). At the end of 2018 it reached 280 GW. The leader was China with 175 GW. The second biggest PV market is located in European Union, especially in Germany (45 GW in the end of 2018). Third place is taken by the North America with the United States covering 90% of installed capacity.

In the future, based on REmap scenario presented by IRENA Asia with the China would still be a leader in global solar PV market. It will be responsible of 65% of the total capacity installed by 2030. North America would be the second largest player in terms of installed solar PV capacity with the level of 437 GW. More than 90% of installation would belong to the USA. Europe would fall to third place with 291 GW of installed capacity in photovoltaic installations by 2030. Such an order among leaders will be maintained until 2050, with a respective increase in power. However, it is predicted that market growth would be shifted also to other parts of the globe – South America and Africa.

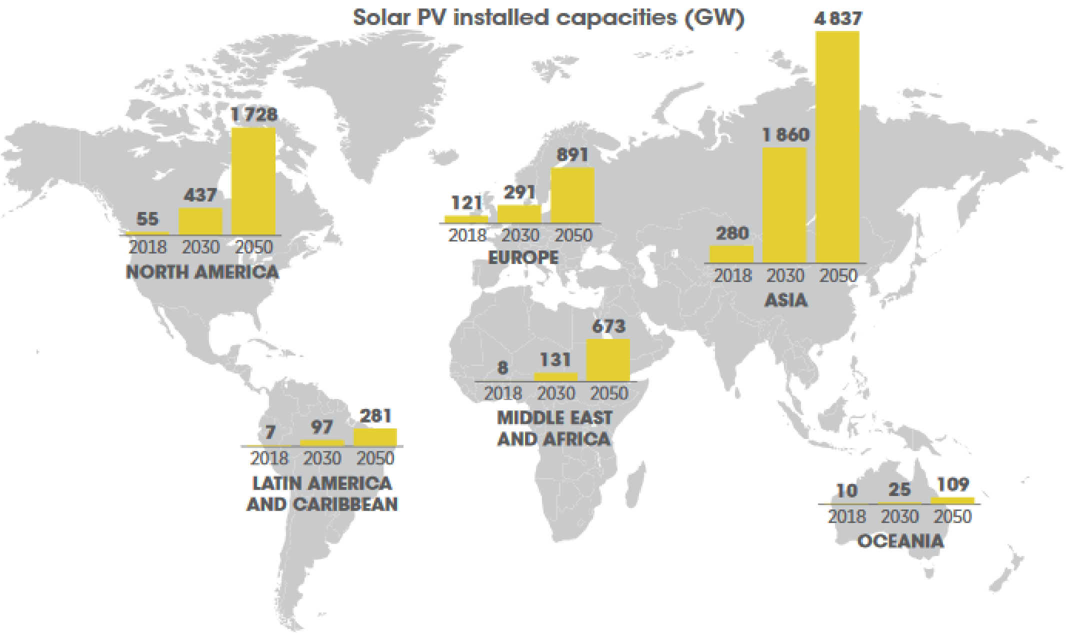


Figure 2.13. Solar PV installed capacities (GW) (Detollenaere et al., 2020)

The PV market is dominated by Si-crystalline poly and mono panels. Other alternative technologies such as Si-amorphous, CdTe and CIGS thin-film, organic and hybrid cells are in development, which can contribute to the production costs reduction. However, currently it is the silicon panels that allow the fastest return of investment. There are many restrictions associated with the implementation of alternative PV technologies. Among others they use toxic elements (Cd in CdTe) and rare-critical metals for example In, Ga in CIGS system. As a consequence, the majority of panels available on the market are Si-crystalline panels (51%- Si-poly, 41%- Si-mono). CdTe and CIGS are respectively only 5% and 2% and 1% for PV panels produced using other materials (dye-sensitized, CPV, organic hybrids) (IRENA and IEA-PVPS, 2016), (Padoan, 2019).

A large increase in new photovoltaic installations is recorded in Portugal. The total installed capacity of PV in the Portuguese market reached 1030 MW at the end of 2020. The country's installed PV base covers around 3% of total national power demand. However, this percentage is expected to grow significantly in the years ahead, as the Portugal has plans to achieve carbon neutrality by 2050 and aims to meet 80% of its total power demand from clean energy generation by 2030. In order to achieve these targets, the Government aims to harness the solar potential and targets solar PV capacity installation to be 1.6GW in 2021 and 8.1GW-9.9GW by 2030.

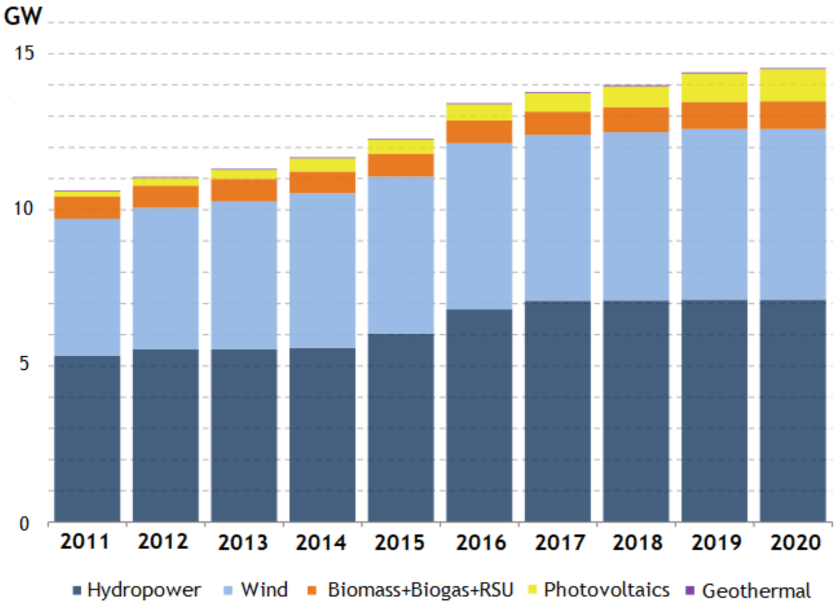


Figure 2.14. Power capacity in renewable technologies in Portugal (DGEG, 2020)

Photovoltaics is the technology that has grown the most since 2011 in Portugal, reaching the installed power of 1030 MW at the end of 2020. That means that over the past decade or so, it has expanded its cumulative PV installations by an average annual growth rate of more than 50%. The figure 2.14 shows how the power capacity of individual renewable technologies has changed over the years (DGEG, 2020).

However, the solar PV module market is developing very strongly. This growth would slow down due to the coronavirus outbreak. Nevertheless, it is predicted that the c- Si market share will decrease in favour of third-generation panels between 2014 and 2030 from 92% to 44.8%. Thus, the share of third generation panels will increase from 1% to 44.1% in the same time (Chowdhury, 2020). Figure 2.15 shows the share of individual PV technologies over the period from 2014 to 2030.

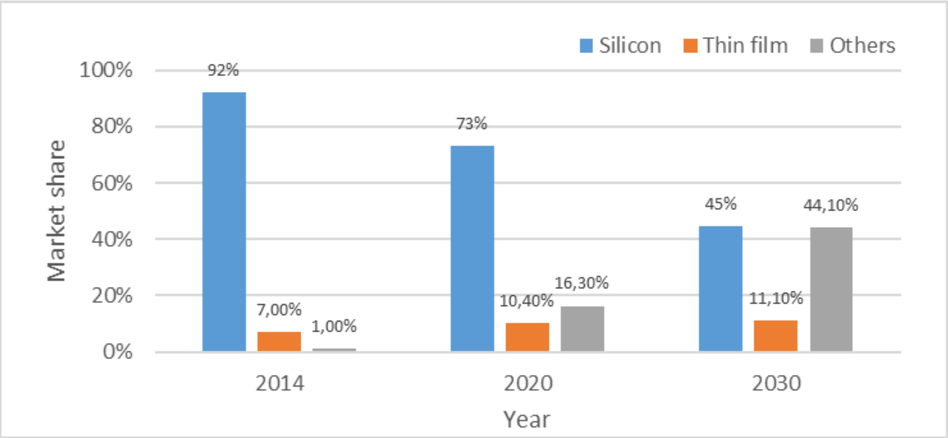


Figure 2.15. PV market share by technology type (2014-2030) (Chowdhury, 2020)

It is visible that currently silicon panels do not have significant competition among 2nd and 3rd generation modules. However, this will change and in 2030 their share will be at the same level as 3rd and newer technologies of PV solar modules. Therefore, the material pattern use will change.

2.4. Material requirements and supply risk

As mentioned before, there are many different photovoltaic technologies. However, some of them have mainly dominated the market and they maintain their leading role for the next 30 years. There are PV panels such as (Carrara et al., 2020):

- wafer-based crystalline silicon (c-Si), both single and multi-crystalline silicon;
- cadmium telluride (CdTe);
- copper indium gallium diselenide (CIGS);
- amorphous silicon (a-Si).

Since these technologies have the greatest commercial significance, the analysis in the following sections will be devoted for the modules consisting of these two types of cells, because they consume the greatest amount of raw materials.

Materials used for the production of photovoltaic systems can be divided into two groups: required for PV cell production and for an additional system (balance of system). The relevant raw materials include various base, precious and minor metals and composite materials. Many of them are of strategic importance to the European Union economy.

The table 2.1 presents the materials together with their application in the solar PV system.

Table 2.1. General materials and their application in PV installation (Blagoeva, 2020)

Material	**Application**
BOS	
Concrete	System support structures.
Steel	System support structures.
Plastic	Environmental protection.
Glass	Substrates, module encapsulation.
Al	Module frames, racking, supports.
Cu	Wiring, cabling, earthing, inverters.
PV cell	
Si	c-Si and a-Si technologies
Ag	c-Si technologies
Ge	a-Si technologies
Cd	CdTe technologies
Te	CdTe technologies
Cu	CIGS technologies
In	CIGS technologies
Ga	CIGS technologies
Se	CIGS technologies

It can be seen that the construction and operation of photovoltaic cells require a variety of raw materials. Solar PV power plants use significant amounts of mineral materials commonly used for structural support and transmission of electricity, including aluminium, concrete, copper, glass, nickel, steel, and zinc. Silica, which is a base for the production the cells, is abundant and available, as well as copper, which also plays an important role. However, thin-film photovoltaic cells are composed of some less common mineral materials, especially metals that are highly valued, because of special properties regarding durability, light absorption capacity and conversion rate to electricity. Those metals that were already listed in table 1 are cadmium selenium, gallium, germanium, indium and tellurium (Bleiwas, 2010). Metals demand in PV production is presented in figure 2.16.

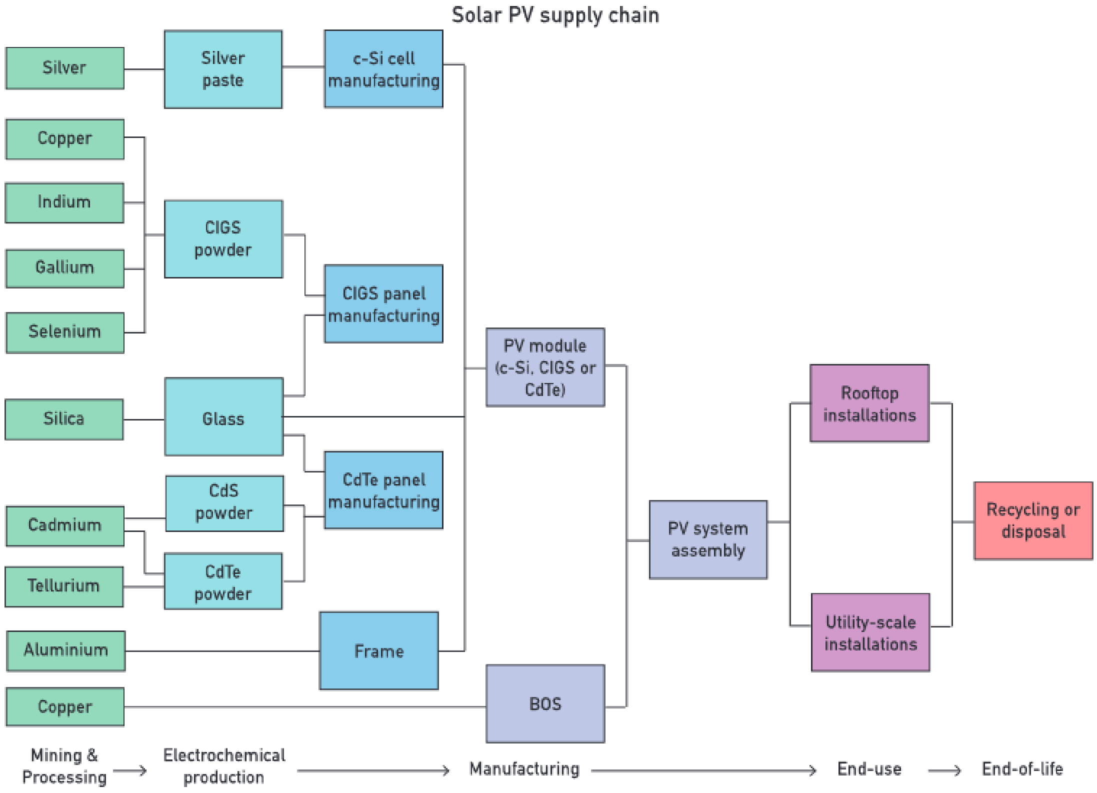
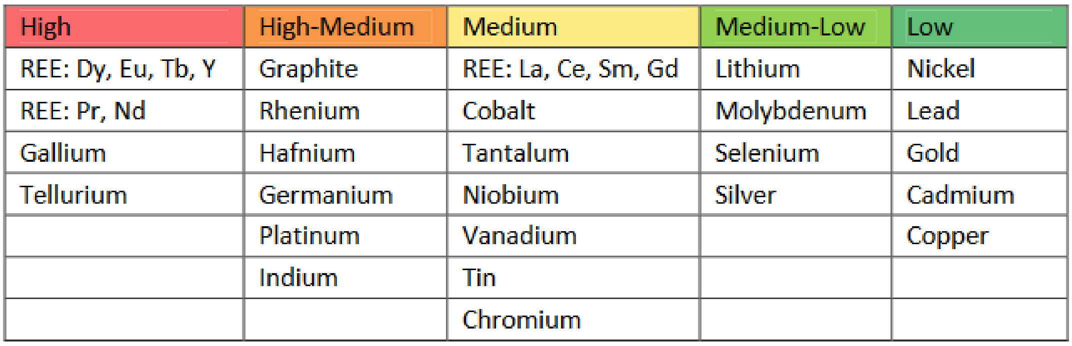


Figure 2.16.. Key metal requirements for solar PV (Teske, 2019)

Three of presented above raw materials (Gallium, Indium and Silicon Metal) were identified as critical among 27 others in the report prepared by the European Commission (EC, 2017). According to this report, a raw material is treated as critical if it presents a high economic importance and it is associated with a high supply risk. Other metals, that are significant for European metals demand for EU energy sector have been also analysed in terms of their criticality taking into account a combination of market and geopolitical factors. As a result, the following table (figure 2.17) was obtained (Moss et al., 2013).



High	High-Medium	Medium	Medium-Low	Low
REE: Dy, Eu, Tb, Y	Graphite	REE: La, Ce, Sm, Gd	Lithium	Nickel
REE: Pr, Nd	Rhenium	Cobalt	Molybdenum	Lead
Gallium	Hafnium	Tantalum	Selenium	Gold
Tellurium	Germanium	Niobium	Silver	Cadmium
	Platinum	Vanadium		Copper
	Indium	Tin		
		Chromium		

Figure 2.17. Criticality ratings of shortlisted raw materials (Moss et al., 2013)

Solar PV is a large end market for tellurium (40%), gallium (17%), indium (8%) and silver (9%) (Dominish et al., 2019). Moreover, it is visible that Gallium, Tellurium, Indium, Silver, Cadmium and Copper are strategic materials for renewable energy sector development.

Rating presented in figure 2.17 from the report on Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector should be seen as the possible supply-chain bottlenecks that may occur under normal business conditions because, they are associated with various types of uncertainty.

Table 2.2 presents a current annual production rates, reserves and resources of metals used in PV production, based on US Geological Survey data (Dominish et al., 2019).

Table 2.2. Production rates, reserves and resources for key metals in PV (Dominish et al., 2019)

Metal	Annual production [t]	Reserve [t]	Resources [t]
Aluminium	60,000,00	30,000,000,000	55-75,000,000,000
Cadmium	23,000	500,000	6,000,000
Copper	19,700,000	790,000,000	3,500,000,000
Gallium	315	110,000	1,000,000
Indium	720	15,000	47,000
Manganese	16,000,000	680,000,000	Unknown
Selenium	3,300	100,000	171,000
Silver	25,000	530,000	1,308,000
Tellurium	420	31,000	48,000

It should also be added that the EU economy and industry depend on international markets that give us the access to important raw materials that are produced and supplied by third countries. Unfortunately, in most cases the EU depends on imports from non-EU countries. The leader is China, which is the main supplier of the critical raw materials responsible for 70% of their global supply and 62% of their supplies to the EU (e.g. rare earth elements, magnesium, antimony, natural graphite). A good way to reduce the risks associated with concentration of production is in many cases compounded by low replacement and low recycling rates. In addition, low substitution and low recycling use increase the risks related with the concentration of production.

As the interest in solar PV technology increases, the demand for these metals will increase. There are concerns that the availability of mineral materials will be able to restrain the rate of growth and its size.

Therefore, the questions arises, will PV technology and its development, which is a promising solution contributing into transformation towards circular economy be constrained by metal scarcity? (Ayres, 2002), (Teske, 2019). Or will there be a need to implement new recycling-based solutions to meet the demand for these minerals?

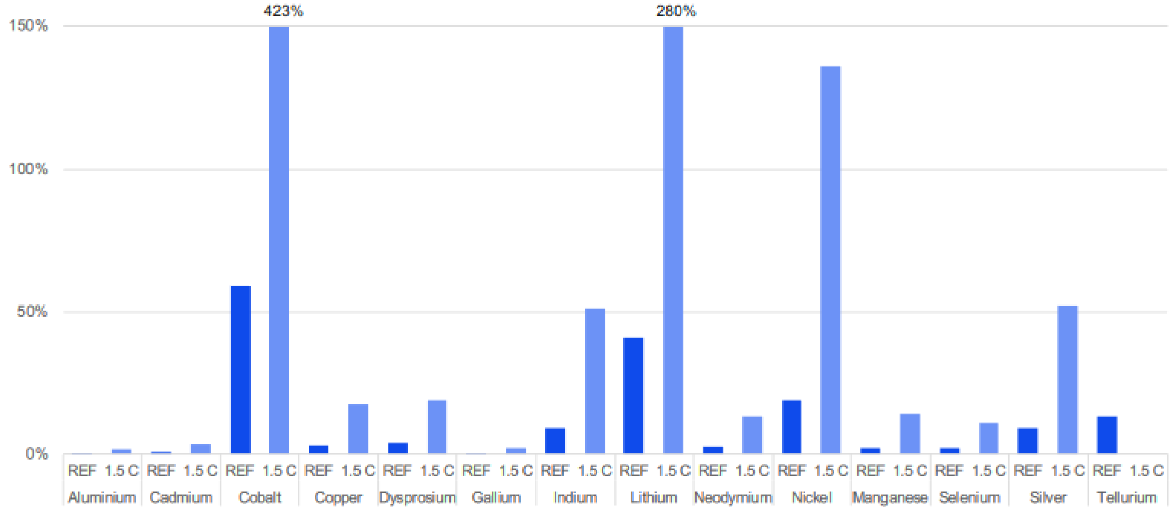


Figure 2.18. Cumulative total global demand from renewable energy and storage by 2050 compared to reserves in the 1.5 degree and Reference scenarios (Dominish, 2019)

Figure 2.18 presents total demand for metals implemented in renewable technologies based on reference scenario and 1.5 degree scenario. It shows that according to 1.5 degree scenario demand for indium, silver and tellurium could reach over 50% of reserves for indium, silver and tellurium. This scenario accounts material demand for high levels of solar PV and wind power, which deliver 2/3 of electricity by 2050, as well as batteries for electric passenger cars, commercial vehicles, buses and stationary storage. Therefore, to meet these goals it will be necessary to find alternative sources of metals, especially secondary materials that would come from recycling.

3. From waste to product

3.1. Photovoltaic waste

Although the development of renewable energy, including the one using solar energy is significant in the transition to low-emission economy, it also entails challenges related primarily to the supply chain and management of used modules. In the near future, strategies for managing of end-of-life modules will play an important role in providing a sustainable photovoltaic sector, which is associated with the implementation of appropriate recovery and recycling procedures and the selection of appropriate technologies that will that will process waste from decommissioned solar PV plants (Sica et al., 2018).

The European Union is a pioneer in terms of regulations regarding PV wastes. According to the Waste Electrical and Electronic Equipment (WEEE) Directive (DIRECTIVE 2012/19/EU) that entered into force in 2012. It includes specific requirements for waste management and recycling and recovery targets, PV panels are defined as e-waste. It aims to promote more efficient exploitation of natural resources by use of secondary raw materials. This directive obliges solar cells manufacturers to implement special waste management programs, in which manufacturers takes the extended responsibility for collecting and recycling end-of-life solar PV panels that are in service in Europe in order to ensure that the PV panels do not pose a threat to the environment (IEA and IRENA, 2016).

Solar PV waste management is anticipated to become an important part of the supply chain, because end-of-life recycling can be a source of valuable materials that may be reused in the production of new solar PV modules or sold into global commodity markets, which will increase the security of future supplies of raw materials.

Preliminary forecasts prepared by International Renewable Energy Agency and International Energy Agency (IEA and IRENA, 2016) take into account two scenarios: regular-loss, which assumes a 30-years lifetime with no early attrition and early-loss, which allows “infant”, “mid-life” and “wear-out” failures before the end of the 30-year lifetime. The figure 3.1 presents panel waste projections in 2015-2050.

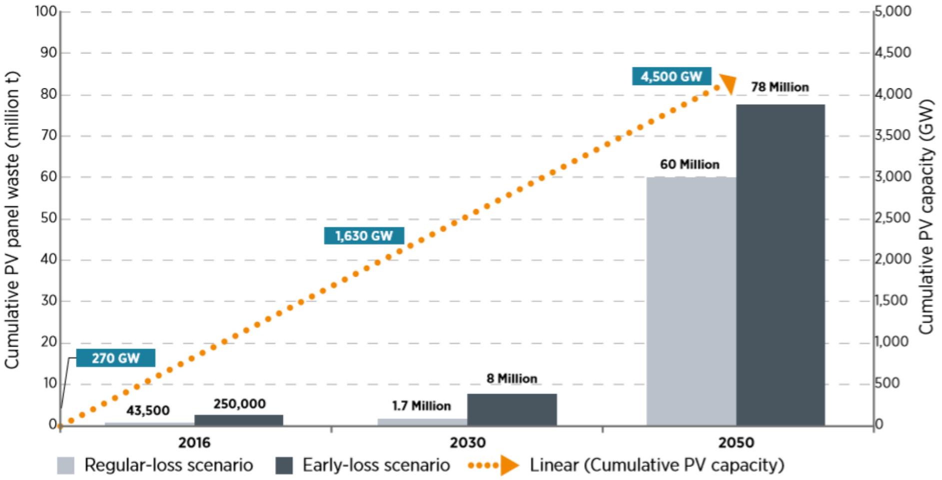


Figure 3.1. Overview of global PV panel waste projections in 2016-2050 (IEA and IRENA, 2016)

It is visible that the volume of decommissioned PV panels was expected to reach 43,500-250,000 million tonnes in the end of 2016 with an increase projected to 1.7 million-8 million tons (t) in 2030. More drastic rise is foreseen for 2050 with the value of 60-78 million t.

The ratio of new PV installations to PV waste is going to increase in the future. In 2020 it will reach the level of 5 %, but in 2050 it will approximately rise over 80% (Figure 3.2).

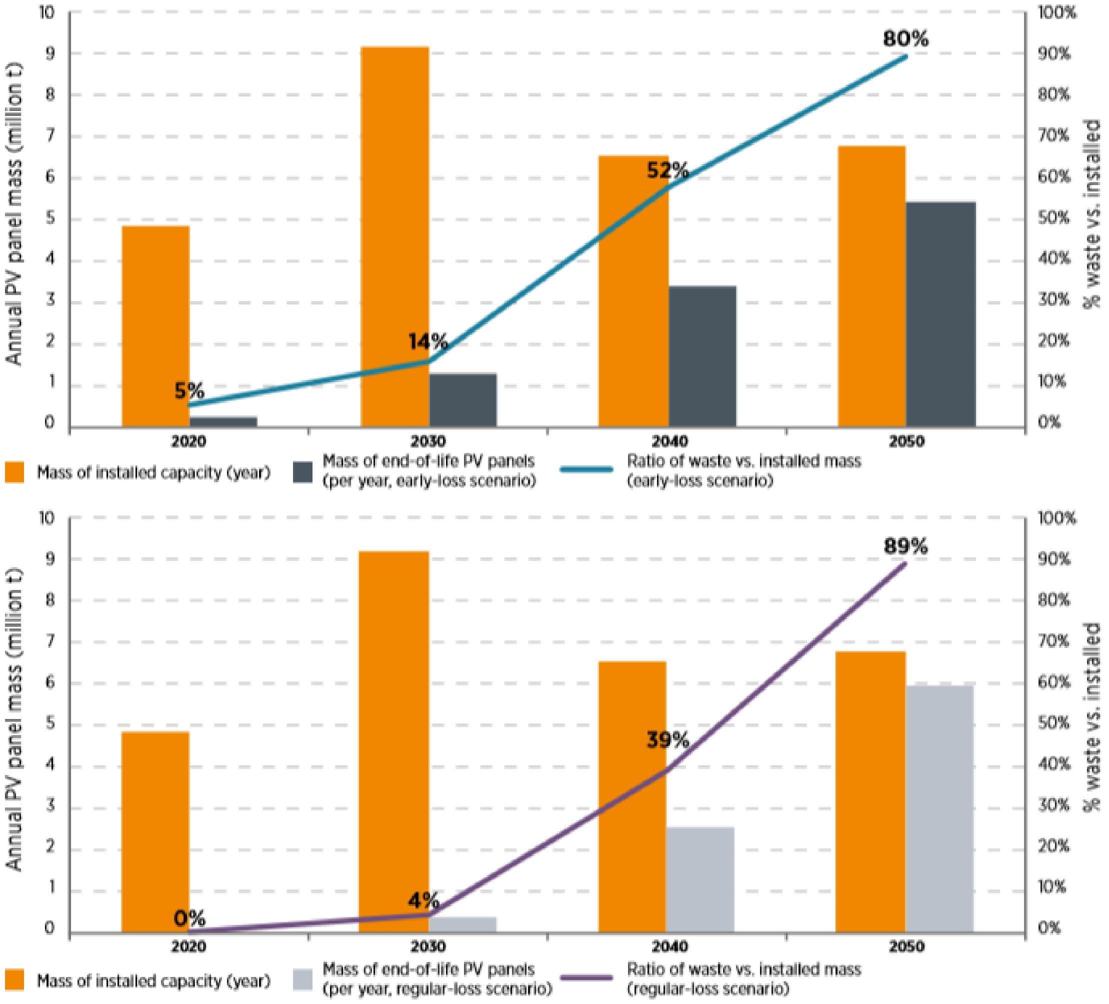


Figure 3.2. Annually installed and end-of-life PV panels 2020-2050 (in %waste vs. t installed) by early-loss scenario(top) and regular (bottom) (IEA and IRENA,2016)

IRENA's report assumes that real future PV panel wastes will most likely reach the value somewhere between the regular-loss and early-loss values.

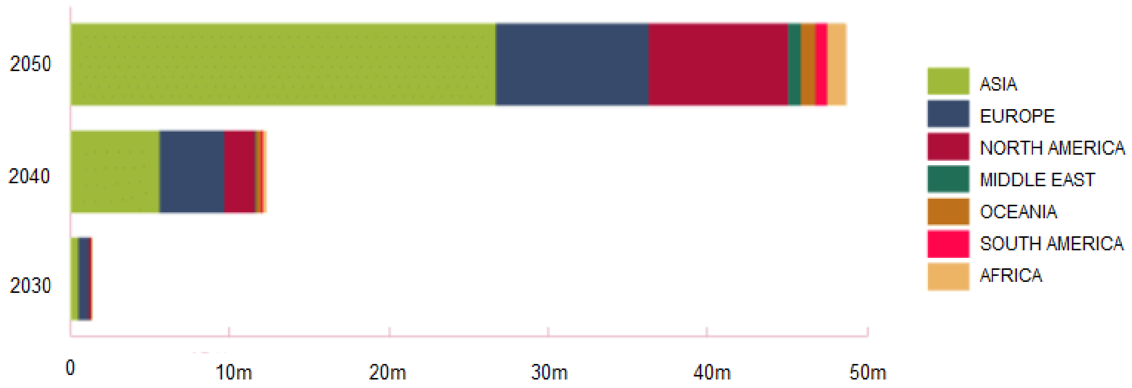


Figure 3.3. Estimated PV waste volumes by continent (Vekony, 2020)

The graph presented in figure 3.3 shows the amount of waste from solar PV farms divided into continents. It is visible that Asia would have the largest share in the generation of PV waste in coming years, which is related to the fact that it produces the largest amount of energy from the sun. There are also many PV manufacturers on the Asian market, which provide technologies for the rest of the World. It is which is the larger producer of energy from photovoltaics which also corresponds to the largest energy production from solar PV panels. Europe ranks second and is followed by North America.

It is foreseen that material influx that would come from recycling of end-of-life modules would allow to produce 2 billion new panels by 2050, which corresponds to 630 GW of new, extra capacity (NREL, 2016).

3.2. End-of-life modules management

Although photovoltaic panels are a great alternative to conventional energy, they carry some issues. Increased interest in PV modules. The growing interest in panels implies increased production of PV modules and huge amounts of devices distributed through the market. Therefore, it will be necessary to implement appropriate strategies that will solve the issues of managing the volume of decommissioned PV panels.

Standard PV management starts from PV waste collection and transfer to location where special treatment takes place, as it is presented in figure 3.4. First treatment step includes separation and division of wastes into material groups. Then, the appropriate materials are recovered and recycled. In the last step, there is a disposal of non-recyclable and non-recoverable components (NREL, 2016).

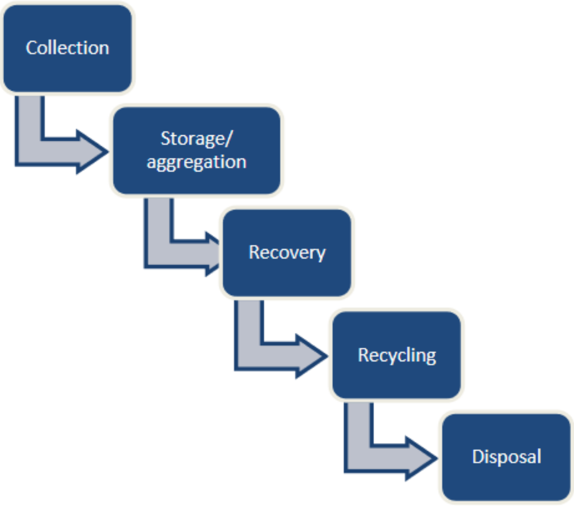


Figure 3.4. Waste management process for the recycling of PV panels (IRENA and IEA-PVPS, 2016)

The following section will discuss solutions that are promoted by the circular economy and focus primarily on reducing material consumption, module degradation and recycling of end-of-life modules. The main idea is the 3R principle - reduce, reuse and recycle, that may be applied to photovoltaics. Figure 3.5 presents the hierarchy of possible actions related to PV waste management according to circular economy concept.

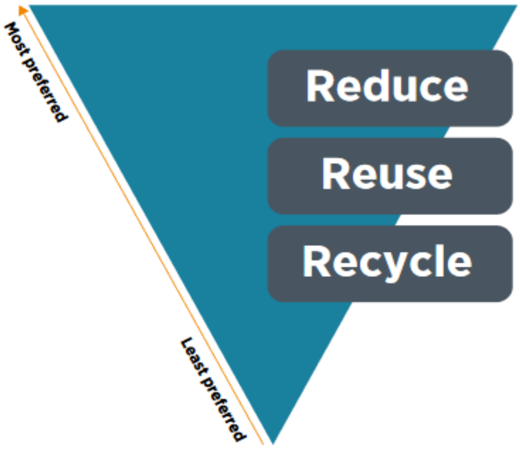


Figure 3.5. Preferred option for PV waste management according to Circular Economy concept (IRENA and IEA-PVPS, 2016)

Such a waste management strategies takes into account the life cycle of a given product. Figure 3.6 presents a process flow diagram of the life cycle stages for PV modules and resulting opportunities for reducing, reusing or recycling.

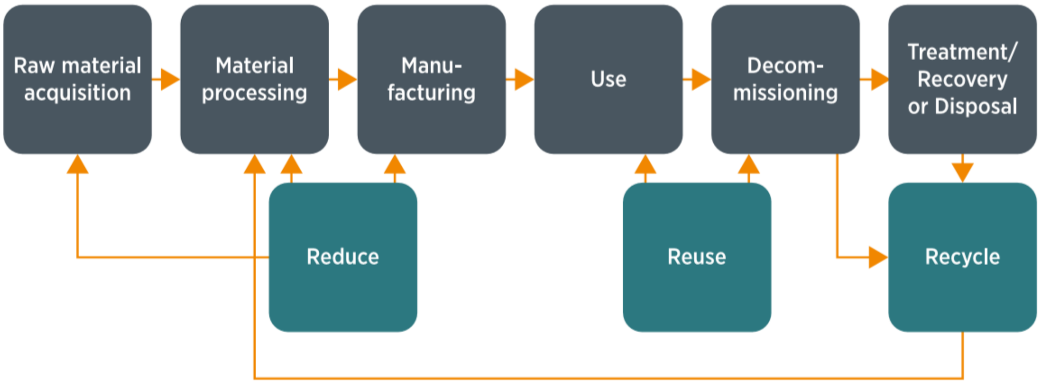


Figure 3.6. Life cycle of PV module and possibilities for 3R implementation, (IRENA and IEA-PVPS, 2016)

End-of-life management is a crucial activity to address large waste volumes and conserve raw materials for the needs of new PV modules manufacturing processes. The three most important strategies included in the 3R Rule are elaborated below (IRENA and IEA-PVPS, 2016).

REDUCE: MATERIAL SAVINGS IN PV PANELS

The goal is to increase the efficiency of the PV panels by reducing the consumption of materials. Due to the great interest in solar energy-based technology and many research, significant progress has already been made in terms of production efficiency and the panels themselves, materials substitution that are caused by scarcity of raw materials and lowering prices of solar PV panels. This principle can also be realized through changing consumer habits and by energy efficiency use of energy.

REUSE: REPAIRING PV PANELS

Solar PV system is an attractive solution in comparison to more and more expensive and depleting fossil fuels. Photovoltaic panels and its components, like all other devices are exposed to damage. Such defects lead to the reduction of the efficiency of the solar PV system. Although it is often more profitable to replace a defective or damaged module with a new one, it is possible to repair the panels. Especially when a defect or imperfection is detected in the early stage of life. However, in the event of replacement, a broken or damaged panel undergoes various tests to check them, and you can perform quality tests to check the electrical safety and output power - such as the characteristics of the instant test and wet leakage test - to recover some value from the panel by resale. Repaired modules are used and resold as replacements or as worn out panels at a reduced market price, and partially repaired panels or components that may be sold on the secondary market, and in this way keep them on the market as long as possible. Old modules may be used for lower demanding applications (e.g. wells in the remote areas, mills).

RECYCLE: DECOMMISSIONING AND TREATMENT OF PV PANELS

Recycling allows to unlock huge amounts of raw materials trapped in PV modules. It is anticipated that extraction of secondary raw materials from end-of-life solar panels can create important value for industry. The lifetime of the typical solar PV module reaches 25-30 years, while inverters around 10 years. The panel performance drops by 6-8 % after 25 years of use (Rapacka, 2019), but it depends on the technology. The first generation of PV panels, that appeared in the 1990s will soon be taken out of use and replaced by newer installations, which creates a challenge for the environment and waste reduction authorities. Therefore, photovoltaic waste recycling can also generate business opportunities. In this way, a new branch of specialists in the PV sector may appear in the future. According to the report of the International Renewable Energy Agency (IRENA) and the IEA-PVPS "End-of-Life Management: Solar Photovoltaic Panels" (IRENA and IEA-PVPS, 2016). Program, recycling or re-use of solar PV panels can release about 78 million tons of raw materials and other materials worldwide by 2050. The recovered raw material can be reintroduced into the economy and saved for the production of new PV panels or other products, thus increasing the security of future PV supplies. Until recently, used or damaged solar PV modules have generally been recycled at glass processing plants. In this case, only glass and aluminium were recovered. Nowadays, special dedicated plants recycling solar PV panels are currently being created, which will also recover other module components - silicon, copper, silver or plastic. In Europe, such a plant is being built by Veolia, with the support of the PV Cycle (organization, which deals with the recycling of solar modules) (GRAMWZIELONE, 2019). Such plants will become especially necessary when PV modules installed in a photovoltaic boom, which began in Europe about 10 years ago, will need to be recycled in 10-15 years. It is also worth adding that the need to collect and recycle used solar PV modules is imposed on their producers and importers by the already mentioned EU WEEE directive (IRENA, 2019).

3.2.1. Recycling rates

It is possible to recycle glass, aluminium and semiconductors. The most popular methods for c-Si modules recycling consists of mechanical, chemical and thermal processes. Even though for the production of thin-film modules less materials are used, there are some materials such as indium, tellurium, cadmium, gallium, selenium and silver which require particular attention, because of their toxicity as well as availability. Moreover, during production processes greenhouse gases are emitted to the atmosphere. Therefore, it is worth looking at the recycling process, which may solve some of these issues.

PV Cycle organisation has recorded recycling rate of 96% for crystalline PV solar cells in 2016. Firstly, the cable, junction box and the aluminium frame were removed from the PV module. In the next step, the module was shredded, sorter and separated in order to send appropriate components to specific recycling processes, what is presented in figure 3.7 (Lunardi et al., 2018).

Figure 3.7. Summary of PV cycle recycling process for c-Si modules (Lunardi et al., 2018)

Most current recycling of PV panels focuses on recycling of glass, aluminium and copper. The other metal components are usually trapped in the glass and polymer encapsulant fractions and require some additional treatments for recovery. Removal of the encapsulant is a really demanding task, because it is designed to last for many years and be resistant to various conditions. Therefore, recovering the small amounts of valuable (silver, copper), scarce (indium, tellurium) or most hazardous materials (cadmium, selenium, lead) is more challenging. The recycling rates for crucial metals are presented in table 3.1.

Table 3.1. Solar PV material intensity and recycling rates (Dominish et al., 2019)

Technology	**All PV**		**c-Si**	**CIGS**			**CdTe**	
Material	**Aluminium**	**Copper**	**Silver**	**Gallium**	**Indium**	**Selenium**	**Cadmium**	**Tellurium**
Current materials intensity [t/GW]	32,000	4,000	20	9	28	41	70	60
Current recycling rate [%]	77%	34%	0%	0%	0%	0%	77%	77%
Potential recycling rate [%]	81%	81%	81%	81%	81%	81%	81%	81%

It can be seen that silver (and metals in CIGS module) is not usually recovered, although it is one of the most valuable metal in a typical PV module, which stands for nearly 50% of the material value (Dominish et al. 2019). However, recycling of PV installations is not a mature industry yet and there is a room for improvement, taking into account that PV modules can be in service approximately 30 years. The volumes of decommissioned solar cells are generally too low to make a recycling economically viable at present. Nevertheless, in the near future it is going to change, because the amount of PV waste will rise, as well as number of new PV installation and the requirements for materials. Therefore, a recycling as a strategy for end-of-life solar PV panel management is gradually becoming a promising solution (Lunardi et al., 2018), (Chowdhury et al., 2020).

3.2.2. Recycling processes

It is possible to find a lot of articles on the recycling processes and techniques for PV solar panels (Klugmann-Radziemska and Ostrowski, 2010), (Tao and Yu, 2015), (Xu et al., 2018), (Lunardi et al., 2018), (Ardente et al., 2019). Several processes for valuable metal recovery from PV wastes has been developed and even commercialized. So far, PV modules have been recycled in glass recycling plants, which recover metal frames and glass parts, other components have gone to disposal. However, nowadays special dedicated facilities are currently in operation or under construction which deal with management of end-of-life solar PV modules and that are trying to make PV recycling as complete and mainstream industry. There are recycling organization, association such as Veolia, PV Cycle or Solar Energy Industries Association (SEIA). Another effort comes from manufacturers, like SunPower and First Solar, which run global recycling programs for their customers, allowing them to return old, end of life solar modules back to the manufacturers in the purpose of recycling.

- Silicon Based Solar PV Panel Recycling

The key approach is to separate the cells from the other parts, so the cells remain intact. The first stage of recycling silicon crystal panels is the dismantling of the end of life panel into aluminium and glass parts. The degree of glass recycling is about 95%. And the aluminium forming the frame entirely is used to re-mold the module frames. Other materials are directed to heat treatment at 500°C to weaken the bonds between individual cells. The plastic encapsulant evaporates in an extreme heat. However, it is used as a heat source for further processing. As a result, silicon cells are obtained ready for further processing. After heat treatment, the green equipment is physically separated. 80% of them can be easily reused and the rest have been improved. Silicon particles - called wafers - are digested with acid. Damaged wafers are melted and then used to produce the new silicone modules, which gives a 85% recycling rate of silicone material (Huang et al., 2017).

Figure 3.8 presents Sankey flow diagram for PV recycling process for PV solar module described in literature. The process is called FRELP (Full Recovery End-of-Life Photovoltaic) and it is a European project, run by Sasil S.p.A., SSV – Stazione Sperimentale del Vetro and PV Cycle. It aims to recover different material fractions embodied into PV silicon module in the most economical way (Lunardi et al., 2018).

The FRELP process involves the recovery of silicon and other metals. Initially, the modules are heated up in a furnace. Then they are subjected to acid and filtration, as a result of which silicon is recovered. Other metals like silver are recovered in electrolysis. The remaining material are primarily polymers, which evaporate as a result of high temperature combustion and thus serve as a source of additional energy.

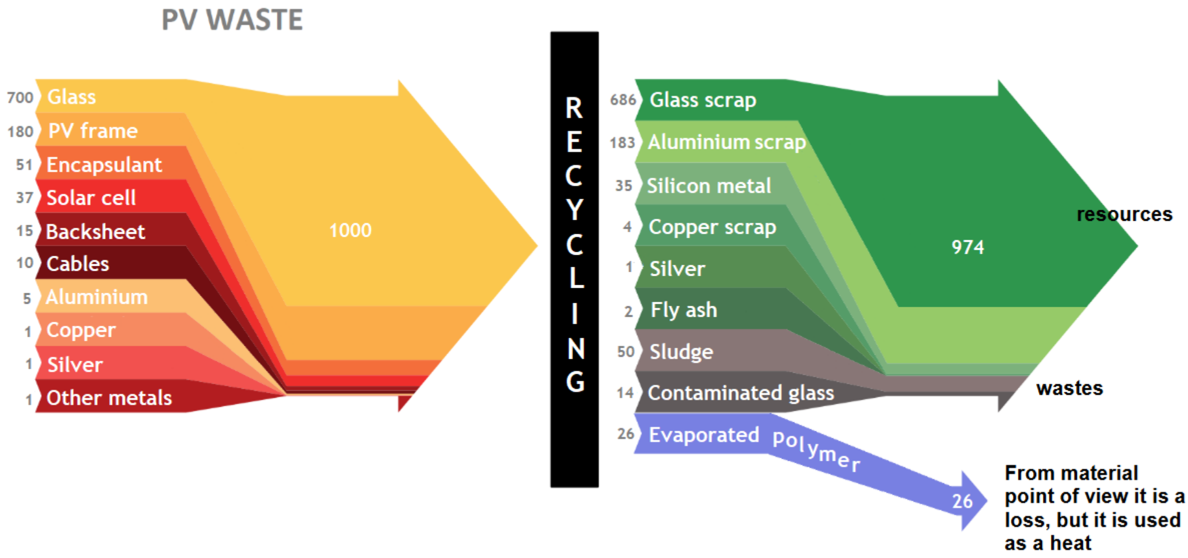


Figure 3.8. Sankey diagram of recycling process for 1000 kg of PV waste based on FRELP project (Mathur et al., 2020), (Latunussa et al., 2016)

It is seen that output materials from the FRELP process may be treated as resources, which can be used for the production of new PV panel or other technologies. However, this process is not 100%

efficient. Some components have to be managed in other way, such as disposal. Hazardous sludge comes from acid leaching, ash is a result of the fluorine reduction in the furnace and contaminated solar glass contains non-glass fractions. Some amount of material is lost in a form of nitrous oxide that is created in the electrolysis process (Bomgardner and Scott, 2018), (Ardente et al., 2019).

In summary, recycling of c-Si modules includes division of c-Si glass, silicone cells recovery and the other metals. It is necessary to separate the layers of monocrystalline panel layers. Such a procedure requires removal of the encapsulant from the module and Si cells in order to recover metals. It is a difficult operation and there are many possible approaches, including thermal, mechanical and chemical processes. Chemical methods capture metals via digestion and other processes. In the next step, substrate glass and metals in semiconductors are separated, recovered and purified (Chowdhury et al., 2020).

- Thin-Film Based Solar PV Panel Recycling

Recycling processes applied for thin-film modules differ from those methods implemented for c-Si panels that result from differences in the construction of the modules. The first method that was used on a larger scale in the industry was established by the First Solar company for CdTe panels (Rocchetti and Beolchini, 2015). In this method, the PV modules after collection are transported to the special facility and shredded. After that, they are crushed in a hammer mill (Redlinger et al., 2015).

Therefore, the recycling process for thin-film modules is more drastic. When all particles have a size of 4-5mm, lamination that keeps all materials together breaks and can be removed. The remaining parts consists of both solid and liquid material. In order to separate them a rotating screw is used. The solid parts rotate inside a tube and the liquid pour into a special container.

To ensure purity, liquids goes through a dewatering process and precipitation. The last step is metal processing, which provides a separation of different semiconductor materials. It is it depends on the panel production process, but on average about 95% of the semiconductor material is reused. Solid matters are contaminated with so-called interlayer materials, which are lighter in mass and can be removed through a vibrating surface. Finally, the material goes through rinsing. What is left behind is pure glass, saving 90% of the glass elements for easy re-manufacturing (Lunardi et al., 2018), (Vekony, 2020).

The diagram in figure 3.9 shows a summary of recycling processes for silicon and thin-film modules described above.

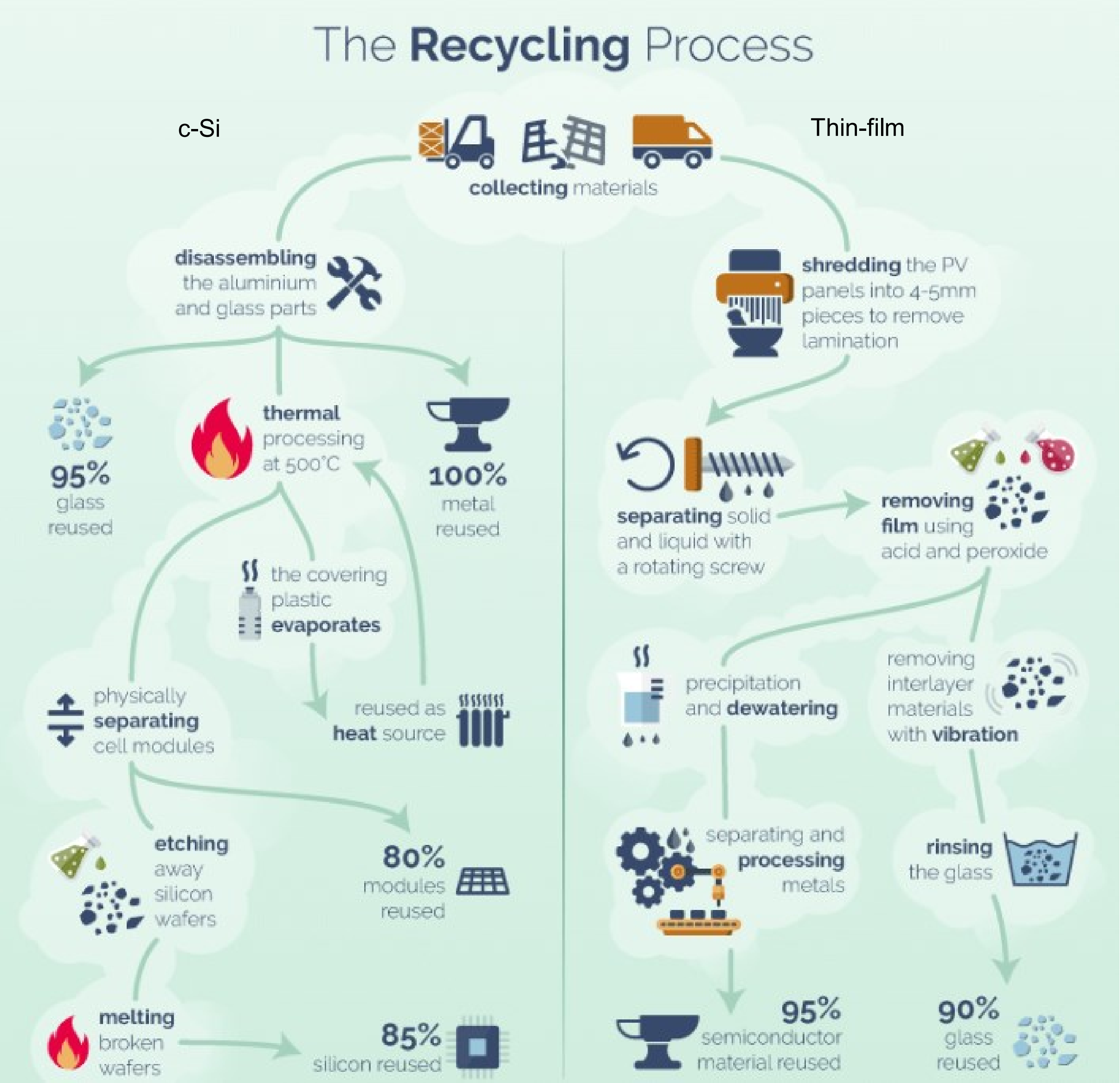


Figure 3.9. Diagram of the recycling processes for silicon and thin-film modules (Vekony, 2020)

As we can see, the recycling process consumes some goods, such as water or acids. In addition, electricity and heat are consumed, especially for the separation processes, as well as fuel and other additional materials. Thus, recycling allows valuable materials to be recovered, but at the same time consumes other goods. Therefore, we have to remember that the recycling process impose some environmental burden.

4. Material requirements analysis

4.1. Approach and data

In this section, a material analysis of all components required for the production of photovoltaic modules up to the year 2100 was carried out using data provided by manufacturers and future demand based on the two scenarios. In the first step, the demand for electricity and power capacity in photovoltaic installations were simulated, taking into account the scenarios developed by IRENA and 2.6 RCP scenario (Vuuren, 2011). The goal is to answer the question whether we will be able to provide technologies to meet the future energy demand, taking into account limited resources and regenerative capabilities of the Earth. The possibility of material recovery will also be studied in order to ensure secure material supply, especially metals, which are crucial for the production of PV cells.

Moreover, the following assumptions and simplifications were adopted for the analysis:

- until 2000, only silicon panels are installed
- 25 years lifetime of PV modules
- The first panels put in service in 2000 and the first end of life modules appeared in 2025, it is the moment when the recycling process of solar PV modules begins
- By 2100, 95% of modules implemented in the market stands for silicon crystalline panels, whereas 5% are thin-film panels (including 70% of CdTe and 30% of CIGS modules)
- Only end-of-life modules are recycled

New capacity, in individual years, is the power resulting from the growing demand for the solar electricity, but also it is the power that must be supplemented due to the withdrawal of end of life PV modules

4.2. Lifetime of a solar PV panel

Photovoltaic technology was put into service on a larger scale about 10 years ago. Therefore, no accurate data is yet available regarding plant lifetimes (most of the installed panels are still in their operational phase). Usually, it is assumed that the average lifetime of the PV panel is 25 years. (Fraunhofer ISE, 2020). This value will be taking into account for the calculations.

In order to assess the future demands for the raw materials required for the deployment of PV systems in EU between now and 2050, a policy with relevant electricity generation scenarios were considered. It was taken from the Global Renewables Outlook: Energy transformation 2050 (IRENA, 2020). It is the Planned Energy Scenario (PES) which is based on existing energy system development strategies and planned goals and policies (as of 2019) and the Transforming Energy Scenario (TES), which presents an ambitious, but still realistic, energy transformation that is based on renewable energy sources and constant improvement of energy efficiency. This scenario aims to keep the increase of global temperatures below 2°C towards 1.5°C in this century. It assumes:

Lifetime of the module is limited by damages caused by heat and humidity. Despite initial concerns, thin-film based technology seems to be able to be in service as long as silicon panels or a little bit shorter. Every year efficiency of both technologies drops by 0.5–1%, which corresponds to a 25–40 lifetime (Almosni et al., 2018).

4.3. Power capacity

Future capacity demand has been determined using reports prepared by IRENA (IRENA, 2020) and the RCP 2.6 scenario (Vuuren, 2011) (Representative Concentration Pathways). TES scenario by IRENA assumes that renewable technologies will be dominating the global market in terms of power generation capacity. Solar PV with wind is getting cheaper and will be a base source of electricity in many markets, second scenario assumes that carbon dioxide emissions start decreasing by 2020 and will reach zero by 2100 and it keeps global temperature rise below 2°C by 2100. Both scenarios are presented in Figure 4.1 and Figure 4.2.

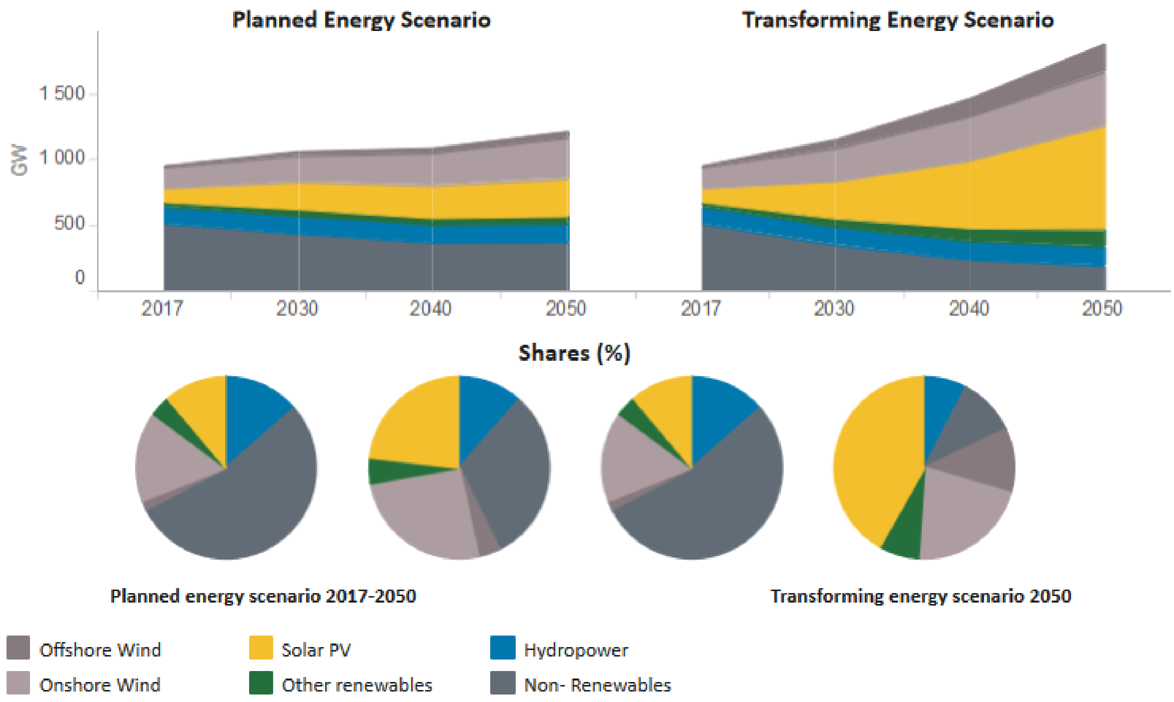


Figure 4.1. Global electricity capacity in PV (2017-2050) according to TES scenario (IRENA, 2020)

Table 4.1. Global electricity capacity in PV (2017-2050) according to TES scenario (IRENA, 2020)

Year	Transforming [GW]
2017	386
2030	3,151
2040	5,760
2050	8,519

It can be seen that energy demand in the future will increase as well as the share of energy supplied using renewable energy sources in TES scenario. In 2050 power capacity installed would reach about 8,5 TW.

For further predictions one of the RCP 2.6 scenarios was used to determine the installed capacity in photovoltaic panels from 2050 to 2100. Set of different RCP 2.6 scenarios regarding primary energy are presented in figure 4.2.

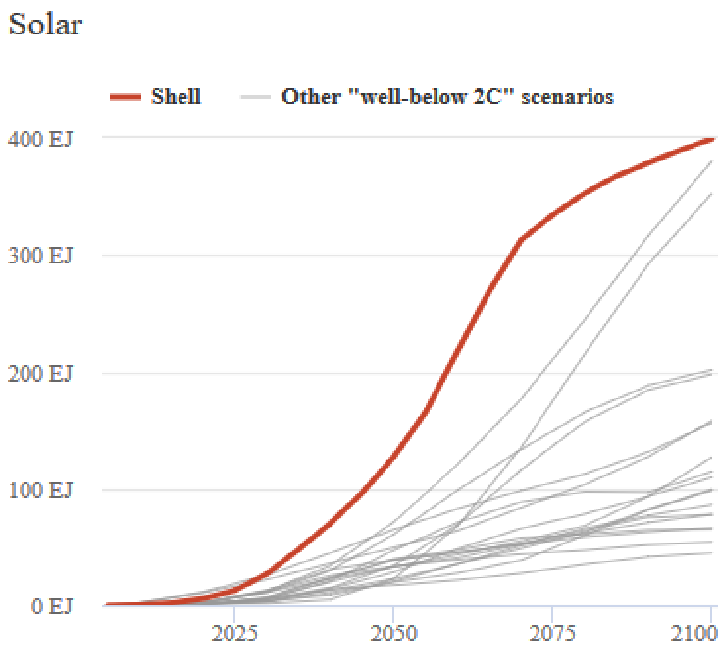


Figure 4.2. Primary energy demand for solar (exajoules, EJ) in Shell's well-below 2C scenario (red) and the RCP2.6 model ensemble (grey) (Evans, 2018)

Based on previously mentioned papers a simulation of electricity demand from PV installations up to 2100 was prepared, which is presented in figure 4.3.

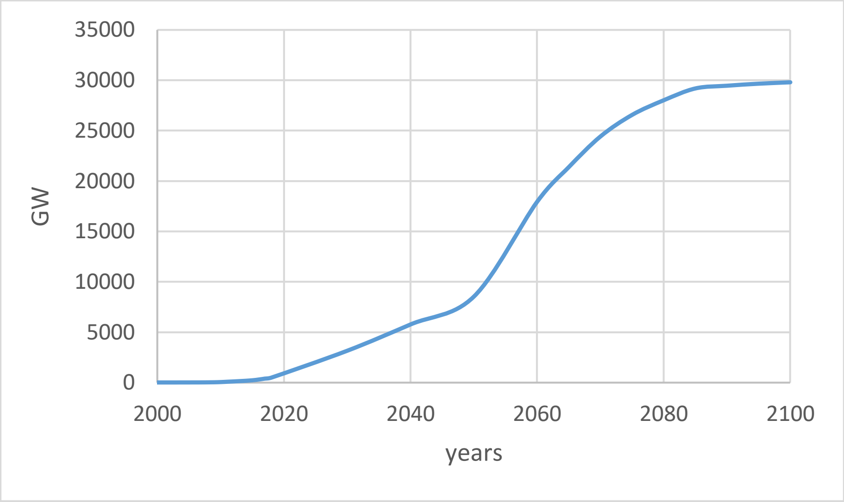


Figure 4.3. Power capacity in PV installation by 2100 (own work)

It can be observed that the biggest growth is foreseen for 2050 and 2060. In 2100 power capacity would reach about 30 TW or even more.

4.4. Material intensity

- Crystalline silicon modules

They are composed of Si wafers of about 200-μm thickness, which play the main role in the production process of electricity. This semiconductor material goes through numerous microfabrication steps before being integrated into the cell and efficiently convert sunlight into electricity. Another part is an Anti-reflective coating (ARC), which covers the p-n junction. ARC is usually composed of a single layer of silicon nitride (SiNx). It cuts down the optical losses due to Si's high reflectivity. Silver (Ag) is a material of surface electrical contacts and Cu ribbons for solar PV cells connections. A double layer of ethylene–vinyl acetate (EVA), which forms the encapsulation. Apart from protection issues, the EVA layer is also used as an adhesive between the glass and the Si wafer. ARC encapsulation and composite glass, which protect the module from damage. Modules are captured in the plastic backing that consists of polyvinyl fluoride (PVF) and polyethylene (PET), in order to make the module weatherproof alongside with aluminium frame. There is also a junction box, which connects different PV modules (Ilias et al., 2018). Typical composition of a c-Si panel is presented in figure 4.4.

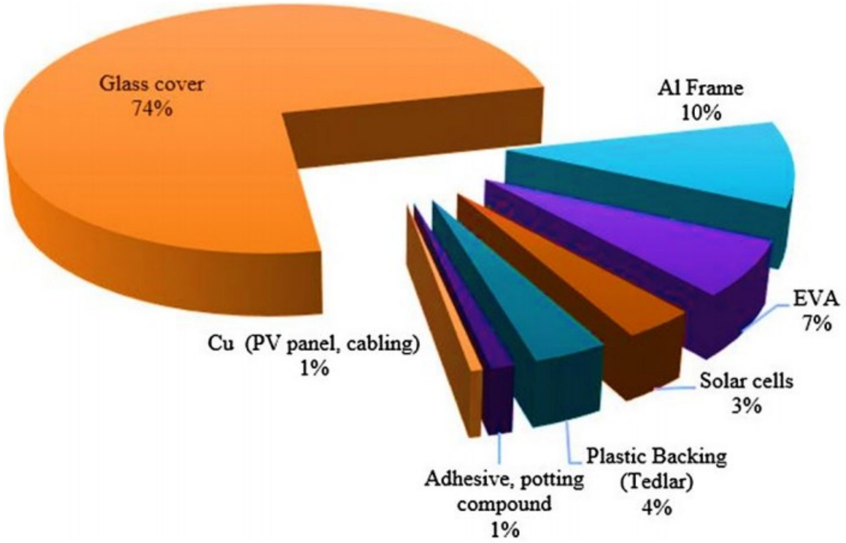


Figure 4.4. A typical c-Si material composition (Ilias et al., 2018)

Crystalline silicon photovoltaic panels available on the market are similar in size. They are composed of cells that are arranged in rows of 6. Such modules usually consist of 48, 60 and 72 cells. According to Columbus Energy S.A., the most common PV modules are made of 60 cells, which are by far most frequently used for household installations due to their good mechanical properties and easy installation.

Obviously, 72-cell panels are larger and heavier. However, if there is a difference in the scale of the installation, this does not have much effect. In this case, the efficiency of the panel is important, which determines the amount of solar radiation reaching the panel that is converted into electricity. Table 4.2

presents data related to the various solar PV technologies prepared on the basis of data presented by the manufacturers of solar PV panels.

Table 4.2. Main features of various photovoltaic silicon crystalline modules based on different manufacturers' data (own work)

Manufacturer	**Sharp**	**Sunport Power**	**SunLink**	**GCL System Integration**	**Bruk Bet Solar**	**Q.Cells**
Cell Type	Mono	Mono	Poly	Poly	Mono	Mono
Efficiency [%]	18.9	19.4	17.1	18.4	18.5	18.6
Maximum power [Wp]	310	315	280	290	380	310
Height [mm]	1,650	1,640	1,650	1,640	1,990	1,670
With [mm]	992	992	992	992	1,005	1,000
Thickness [mm]	35	35	35	35	40	32
Weight [kg]	18.5	18.5	18	18.1	22	18.5
Cell number	60	60	60	60	72	60
Material intensity [kg/W]	0.060	0.059	0.064	0.062	0.058	0.060

From material consumption and sustainability point of view, another parameter may be interesting. It is a material intensity, which in this case is a measure of the materials required for the production of 1 unit of good, which in this case is a photovoltaic module. This indicator was calculated for each PV panel presented in the table above. The material intensity was obtained using the following formula:

$$Material\ intensity\ \left[\frac{kg}{MW}\right] = \frac{weight\ [kg]}{maximum\ power\ [MW]} \qquad \text{Eq. 4.1}$$

The results of the calculations are presented in table 4.3 and converted into kg/MW.

Table 4.3. Material intensity calculation results (own work)

Manufacturer	**Sharp**	**Sunport Power**	**SunLink**	**GCL System Integration**	**Bruk Bet Solar**	**Q.Cells**
Cell Type	Mono	Mono	Poly	Poly	Mono	Mono
Maximum power [Wp]	310	315	280	290	380	310
Weight [kg]	18.5	18.5	18	18.1	22	18.5
Material intensity [kg/MW]	60000	59000	64000	62000	58000	60000

It can be seen that all the panels, regardless of manufacturer and semiconductor type (poly or mono), got a similar result of 60500 kg/MW.

Assuming the average material intensity as 60500 kg/MW and taking into account a composition of typical crystalline silicone PV panel (Teske, 2019) presented in table 4.4 a material intensity for individual component was calculated per one PV module, a photovoltaic installation for one single-family house (4 kW) and for whole Poland, assuming that the entire demand would be covered by photovoltaics (~46 000 MW) (Wysokie napięcie, 2020).

Table 4.4. Material intensity for each PV module's fraction (own work)

Fraction	**Share [%]**	**Material intensity [kg/panel]**	**Material intensity [kg/MW]**	**Material intensity [kg/household installation (36 modules-4kW)]**	**Material intensity [t/power installed in Poland (46 000 MW)]**
Glass	74.00%	13.69	44,770.00	177.97	20,59,420
Polymer	10.00%	1.85	6,050.00	24.05	278,300
Aluminium (Al)	11.08%	2.05	6,703.40	26.65	308,356
Silicon (Si)	4.00%	0.74	2,420.00	9.62	111,320
Copper (Cu)	0.60%	0.11	363.00	1.443	16,698
Silver (Ag)	0.10%	0.02	60.50	0.24	2,783
Zinc (Zn)	0.12%	0.02	72.60	0.29	3,340
Lead (Pb)	0.10%	0.02	60.50	0.24	2,783

- Thin-film technologies

Thin-films modules stand for less than 10% of the total solar PV market. The most popular representatives of thin-film modules are cadmium telluride (CdTe-65%), copper indium gallium selenide (CIGS-25%) and amorphous silicon (a-Si-10%) (Lunardi et al., 2018). These technologies require less material overall than crystalline silicon and provide flexible geometries. For CdTe panels, the composition is 96–97% glass, 3%–4% polymer, and less than 1% semi-conductor materials (CdTe) and other metals (e.g., nickel, zinc, tin). CIGS contain about 88%–89% glass, 7% aluminium, 4% polymer, and less than 1% semiconductor material (indium, gallium, selenium) and other metals (e.g., copper). Figure 4.5 and table 4.5 present the typical structure of thin-film module (Teske, 2019).

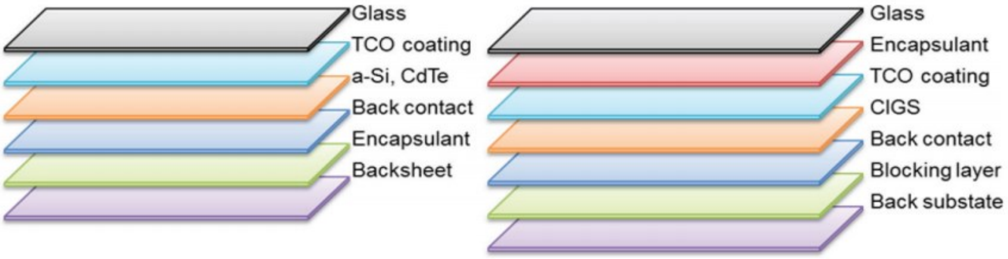


Figure 4.5. Thin-film solar PV module basic structures (Lunardi et al., 2018)

As shown in figure 4.5, the thin-film module is composed of thin layers of semiconducting material (CdTe, CIGS or a-Si) deposited on a substrate (glass, polymer or metal). In Table material composition of thin-film modules is described. The composition of amorphous silicon modules was omitted because their market share is the smallest and the following calculations will be conducted only for CdTe and CIGS modules.

Table 4.5. Thin-film modules composition (Sica et al., 2018)

Fraction	CdTe (%)	CIGS/CIS (%)
Cadmium (Cd)	0.08%	-
Copper (Cu)	0.04%	0.68%
Gallium (Ga)	-	0.01%
Indium (In)	-	0.03%
Molybdenum (Mo)	-	0.12%
Plastic	3.50%	4.00%
Selenium (Se)	-	0.04%
Tin(Sn)	0.05%	-
Tellurium(Te)	0.07%	-
Glass	96.06%	88.00%
Zinc(Zn)	0.05%	0.12%
Lead (Pb)	0.05%	0.00%
Nickel (Ni)	0.10%	-
Aluminium (Al)	-	7.00%

Based on the technologies available on the market and the data presented by the PV module manufacturers, the properties of various thin-film panel models are summarized and presented in the following tables 4.6 and 4.7.

Table 4.6. CdTe modules features from manufacturers data (own work)

Module	Power [Wp]	Weight [kg]	Efficiency [%]	Length [mm]	Width [mm]	Thickness [mm]	Material intensity [kg/MW]
FIRST SOLAR SERIES 4	122.5	12	17	1,200	600	6.8	97,959
RK Solar Inc.	110	12	16	1,200	600	6.8	109,091
Reel Solar Power Inc.	230	25	15	1,400	1100	6.8	108,696
Calyxo	110	12	16.5	1,200	600	6.9	109,091
Mean material intensity							106,209

Table 4.7. CIGS/CIS modules feature form manufacturers data (own work)

Module	Power [Wp]	Weight [kg]	Efficiency [%]	Length [mm]	Width [mm]	Thickness [mm]	Material intenisity [kg/MW]
Eterbright Solar Corporation	120	12.9	14.9	1234	652	35	107,500
PowerMax® SKALA	140	17	13.3	1587	664	38	121,429
Nanosolar, Inc.	260	34.7	13	1937	1034	7	133,462
Solar Frontier K.K	180	18.5	14.7	1257	977	35	102,778
Solartech POWER Inc.	110	12.9	13.7	1234	652	35	117,273
Soltecture GmbH	100	12.6	12.3	1250	650	7	126,000
SOLIBRO SL2 CIGS	145	16.5	15.4	1190	789,5	7.3	113,793
Eterbright Solar Corporation	110	12.9	14.9	1234	652	35	117,273
Mean material intensity							117,438

Necessary data for material intensity calculations come from literature and also consist of manufacturer's data. It was presented in different forms. Therefore, it is normalized to kg/MW. Table 4.8 presents the results material intensity calculations for individual components taking into account the mean material intensity obtained before and converted for one PV module, a photovoltaic installation for one single-family house (4 kW) and for whole Poland, assuming that the entire demand would be covered by photovoltaics (~46 000 MW) (Wysokie napięcie, 2020). The results are presented in tables 4.8 and 4.9.

Table 4.8. Material intensity by component in CdTe technology (own work)

Fraction	**Share [%]**	**Material intensity [kg/panel]**	**Material intensity [kg/MW]**	**Material intensity [kg/household installation (36 modules- 4kW)]**	**Material intensity [t/power installed in Poland (46 000 MW)]**
Cadmium (Cd)	0.08%	0.01	84.97	0.35	3,908.50
Copper (Cu)	0.04%	0.00	42.48	0.17	1,954.25
Tin(Sn)	0.05%	0.01	53.10	0.22	2,442.81
Tellurium(Te)	0.07%	0.01	74.35	0.30	3,419.94
Zinc(Zn)	0.05%	0.01	53.10	0.22	2,442.81
Lead (Pb)	0.05%	0.01	53.10	0.22	2,442.81
Nickel (Ni)	0.10%	0.01	106.21	0.43	4,885.62
Glass	96.06%	11.53	102,024.52	414.98	4,693,128.03
Plastic	3.50%	0.42	3,717.32	15.12	170,996.75

Table 4.9. Material intensity by component in CIGS/CIS technology (own work)

Fraction	**Share [%]**	**Material intensity [kg/panel]**	**Material intensity [kg/MW]**	**Material intensity [kg/household installation (36 modules- 4kW)]**	**Material intensity [t/power installed in Poland (46 000 MW)]**
Copper (Cu)	0.68%	0.088	798.58	3.16	36,734,702.03
Gallium (Ga)	0.01%	0.001	11.74	0.05	540,216.21
Indium (In)	0.03%	0.003	29.36	0.12	1,350,540.52
Molybdenum (Mo)	0.12%	0.015	140.93	0.56	6,482,594.48
Selenium (Se)	0.04%	0.005	46.98	0.19	2,160,864.83
Zinc(Zn)	0.12%	0.015	140.93	0.56	6,482,594.48
Lead (Pb)	0.00%	0.0001	1.17	0.0046	54,021.62
Aluminium (Al)	7.00%	0.903	8220.68	32.51	378,151,344.38
Glass	88.00%	11.352	103345.71	408.67	4,753,902,615.05
Plastic	4.00%	0.516	4697.53	18.58	216,086,482.50

It can be observed that thin-film modules require much smaller amounts of semiconductor for the production of such technologies. However, in the end, the total amount of material to produce the same energy as using silicon modules is greater. This is because thin-film modules are designed for providing smaller amounts of power. Therefore, to provide the same parameters, more panels are required.

In the next step, a simulation of material consumption was prepared in the perspective up to 2100 based on the previously developed results. The consumption of materials was related to the reserves of individual metals, which are crucial for ensuring secure supplies of substrates in the manufacturing process. Mineral reserves are described in table 4.10. Based on literature uses of individual metals were determined along with the share of application for photovoltaics. Then the metal reserves were recalculated taking into account PV metal demands giving the reserves for PV, according to the formula:

$$Reserves\ for\ PV = Resreves\ \times Aplication\ share\ for\ PV \qquad \text{Eq.4.2}$$

Calculation results are presented in the table 4.10.

Table 4.10. Reserves of metals used in PV production (own work)

Material	**Reserves [t]**	**Metal consumption for PV [%]**	**Reserves for PV [t]**
Aluminium	35,000,000,000,000 (USGS, 2018)	10%	3,500,000,000,000
Cadmium	500,000 (USGS, 2014)	7% (Sharma et al., 2015)	35,000
Copper	830,000,000 (USGS, 2019)	10% (USGS, 2018)	83,000,000
Galium	11,000,000 (Lu et al., 2017)	2% (Foley et al., 2017)	220,000
Indium	65,000 (EC, 2014)	8% (EC, 2014)	5,200
Lead	89,000,000 (USGS, 2014)	1% (Midlandlead, 2019)	890,000
Molybdenum	19,400,000 (Henckens et al. 2018)	3% (IMOA)	582,000
Nickel	89,000,000 (USGS, 2018)	5% (Kay, 2018)	4,450,000
Selenium	120,000 (USGS, 2014)	10% (Vulcan, 2010)	12,000
Silicon	no actual data	12% (EC, 2014)	no actual data
Silver	560,000 (USGS, 2018)	9% (Goren, 2012)	50,400
Tellurium	31,000 (USGS, 2019)	40% (Goldfarb et al., 2017)	79,600
Tin	5,500,000 (ITA, 2020)	3% (Kamilli et al., 2017)	165,000
Zinc	225,000,000 (USGS, 2018)	3% (Investor Intel)	6,750,000

It can be observed that silicone and aluminium are the most abundant metal in the earth's crust, which is proven by the size of reserves.

4.5. Depletion of metals

In the next stage of this analysis, the demand for materials and metals was calculated, taking into account the forecast of electricity demand from photovoltaic installations up to 2100. Next, the cumulative material demand was then compared with the available metal reserves, thus giving a metal depletion year, which is presented in table 4.11.

Table 4.11. Depletion of metals used in PV productions (own work)

Fraction	PV requirement up to 2100 [t]	Reserves only for PV [t]	Year (depletion)
Aluminium	510,588,396	3,500,000,000,000	Above 2100
Cadmium	233,905	35,000	2050
Copper	28,183,106	83,000,000	Above 2100
Gallium	13,855	220,000	Above 2100
Indium	34,639	5,200	2050
Lead	4,668,240	890,000	2052
Molybdenum	166,265	582,000	Above 2100
Nickel	292,381	970,000	Above 2100
Selenium	55,421	12,000	2054
Silver	4,520,664	50,400	2020
Tellurium	204,666	12,400	2035
Tin	146,190	5,970	2030
Zinc	5,737,252	6,750,000	Above 2100

It is apparent that the most critical metals in the production of solar PV panels are cadmium, indium, silver, tin, tellurium, selenium and lead. Therefore, further production of new photovoltaic modules will depend on the availability and sustainable management of these metals. Taking into account individual technologies, it is possible to see which metals are bottlenecks that may disrupt the production of new ones in the future. Bottlenecks in overall PV production are presented in figure 4.6.

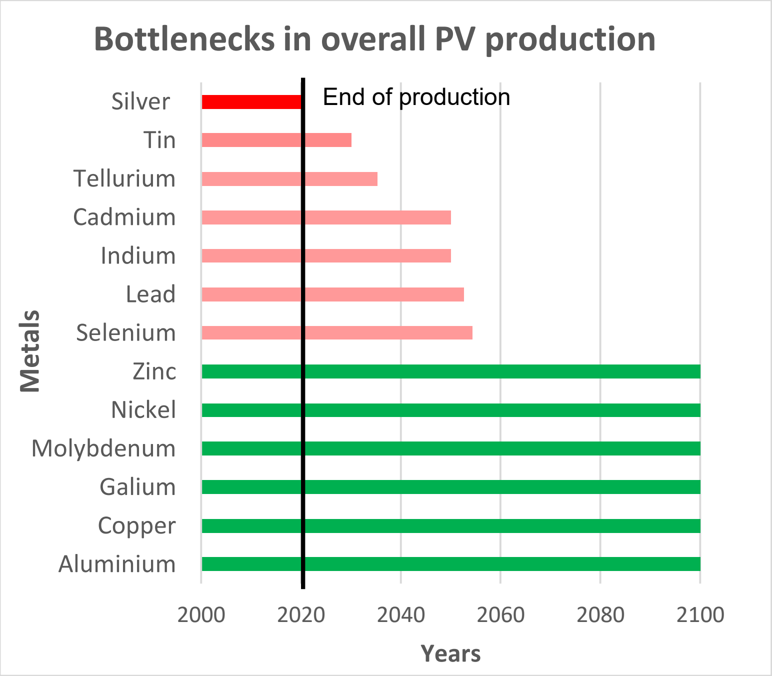


Figure 4.6. Material bottlenecks in the PV manufacturing process (own work)

In the case of c-Si modules, the most problematic metal is silver, which is visible in figure 33. According to the data this analysis, the reserves intended for the production of photovoltaic panels may already run out this year, which can be seen in figure 4.7.

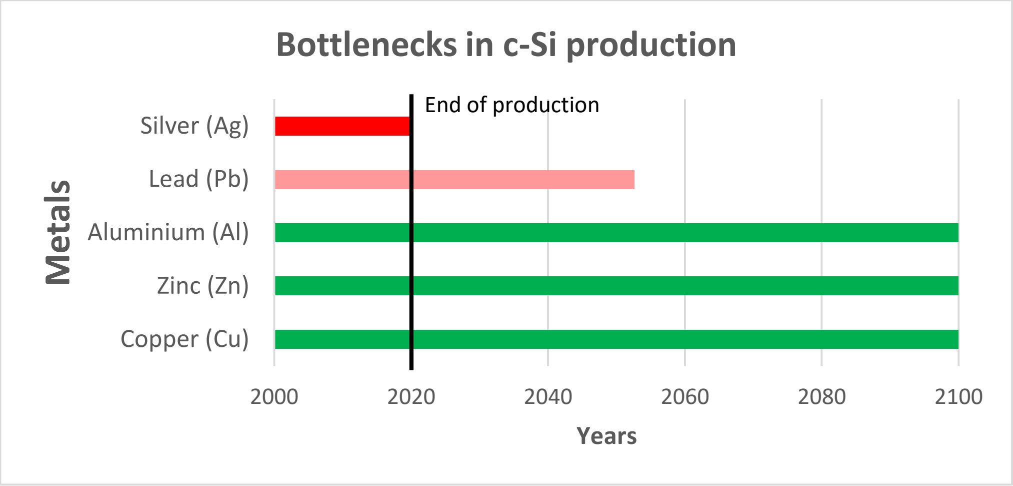


Figure 4.7. Bottlenecks in c-Si module production (own work)

When it comes to thin-film technologies, among CdTe panels, attention must be paid to tin, which may be run out in 2030, as shown in Figure 4.8. In addition, by the year 2100, the Tellurium and Cadmium, the most important metals in the CdTe technology, which act as semiconductors, may also be missing.

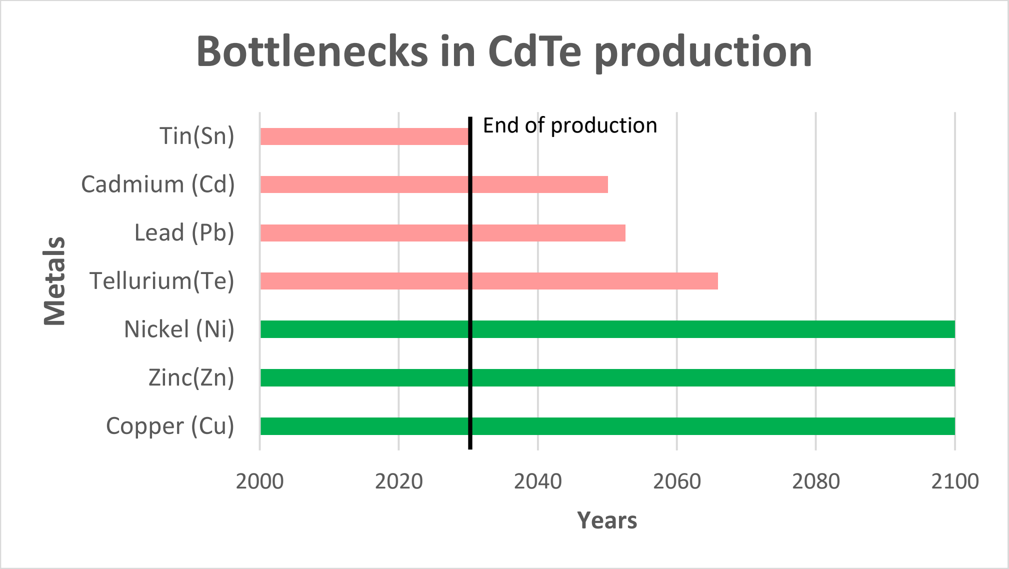


Figure 4.8. Bottlenecks in CdTe module production (own work)

In CIGS and CIS panels, we should be careful about the reserves of selenium and indium, which may run out in the perspective of 2100, what is presented in figure 4.9.

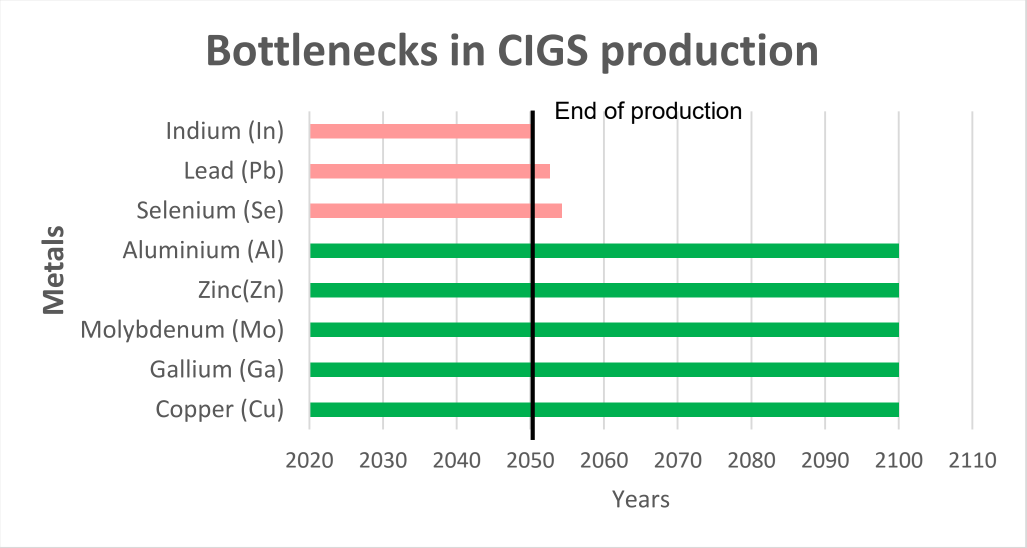


Figure 4.9. Bottlenecks in CIGS/CIS module production (own work)

Other factors are also important for the security of supply of individual metals to solar PV panel manufacturers. The producer of individual metals is of great importance, which usually acts as the importer and how much market share is under his control or whether there are deposits of a given mineral in the country interested in photovoltaic technology. It is also important to know if a given metal may be replaced with another material. If it is possible to use another, more readily available alternative, which resources are unlimited, the production of PVs may be continuous and undisturbed. Table 4.12 contains information that may be useful in defining the strategy and planning the supply of particular metals.

Table 4.12. Supply risk of metals for PV modules(Royal Societyof Chemistry, 2020)

Metal	Recycling Rates [%]	Production (2018) [metric t] (USGS, 2020)	Relative supply risk[1]	Crustal abundance (ppm)[2]	Substitutability[3]	Production concentration[4]	Reserve distribution[5]	Top producer	Reserve holder
Aluminiu	>50%	63,600	4.8	84149	Medium	31%	26%	Australi	Guinea
Cadmium	>10-	25,000	6.7	0.08	Low	32%	20%	China	India
Copper	>50%	20,400	4.3	27	Low	34%	28%	Chile	Chile
Gallium	1-	413 000	7.6	16	Medium	54%	Unkno	China	Unkno
Indium	<10%	835	7.6	0.00003	Low	53%	Unkno	China	Unkno
Lead	>50%	4,560	6.2	11	Unknow	44%	34%	China	Australi
Molybden	>25-	297 000	8.6	0.8	High	40%	43%	China	China
Nickel	>50%	2,256	6.2	26.6	High	17%	36%	Russia	Australi
Selenium	<10%	2,810	7.1	0.13	Unknow	35%	22%	Japan	Russia
Silicon	>50%	7,400	-	282000	-	-	-	China	-
Silver	>50%	27,000	6.2	0.055	Low	19%	23%	Mexico	Peru
Tellurium	<1%	460		0.001	Medium	25%		Europe	Peru
Tin	>50%	318 000	6.7	1.7	Unknow	46%	31%	China	China
Zinc	>50%	12,500	4.8	72	Low	30%	22%	China	Australi

To reduce the consumption of natural resources, the concept of a circular economy is implemented, which assumes that materials and raw materials should remain within the economy as long as possible and the generation of waste should be minimized as much as possible. That is why waste recycling is used, which has many ecological and economic benefits. Via recycling, it is possible to recover raw materials and save other natural goods, which are usually non-renewable. Apart from limiting the use of natural goods, the consumption of energy is reduced, as well as the water and greenhouse gas emissions. It is also worth adding that recycling saves energy because the producer does not have to produce from natural resources. By using recycled materials, we can save on energy consumption, which is a burden on production costs.

Therefore, this part of the analysis focuses on the material-saving effects of recycling end of life PV modules. In the graphs presented in figures 4.10-4.16, for individual strategic metals (those whose availability by 2100 may be at risk), simulations were made of the impact of different recycling rates on

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[1] **Relative supply risk-**An integrated supply risk index from 1 (very low risk) to 10 (very high risk). This is calculated by combining the scores for crustal abundance, reserve distribution, production concentration, substitutability, recycling rate and political stability scores

[2] **Crustal abundance (ppm)-**The number of atoms of the element per 1 million atoms of the Earth's crust.

[3] **Substitutability**- The availability of suitable substitutes for a given commodity.

[4] **Production concentration**- The percentage of an element produced in the top producing country. The higher the value, the larger risk there is to supply.

[5] **Reserve distribution-** The percentage of the world reserves located in the country with the largest reserves. The higher the value, the larger risk there is to supply.

demand for new minerals. The graphs also contain the lines which represent material consumption of metals without recycling and their reserves.

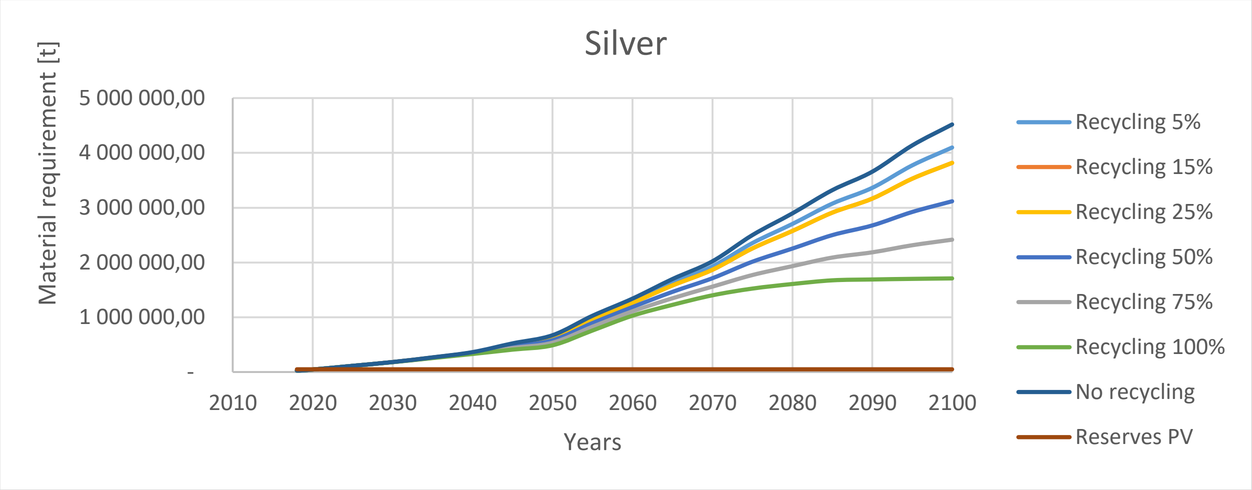

Figure 4.10. Recycling impact on Silver consumption for PV production (own work)

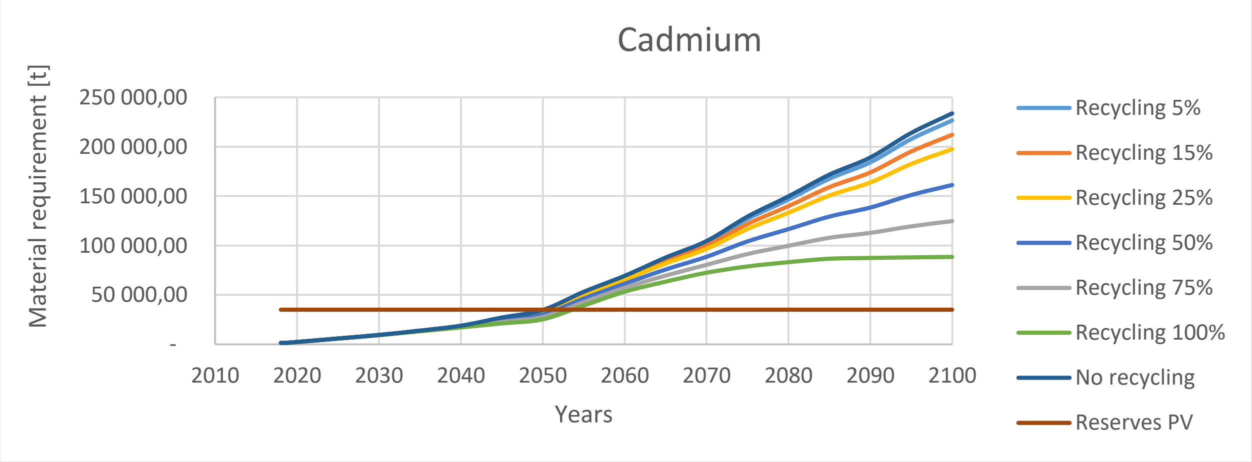

Figure 4.11. Recycling impact on Cadmium consumption for PV production (own work)

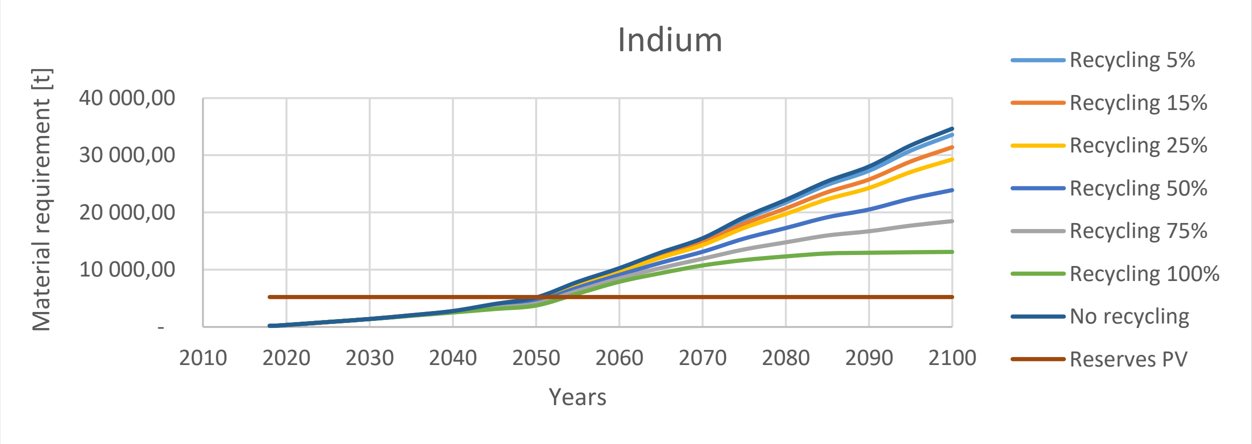

Figure 4.12. Recycling impact on Indium consumption for PV production (own work)

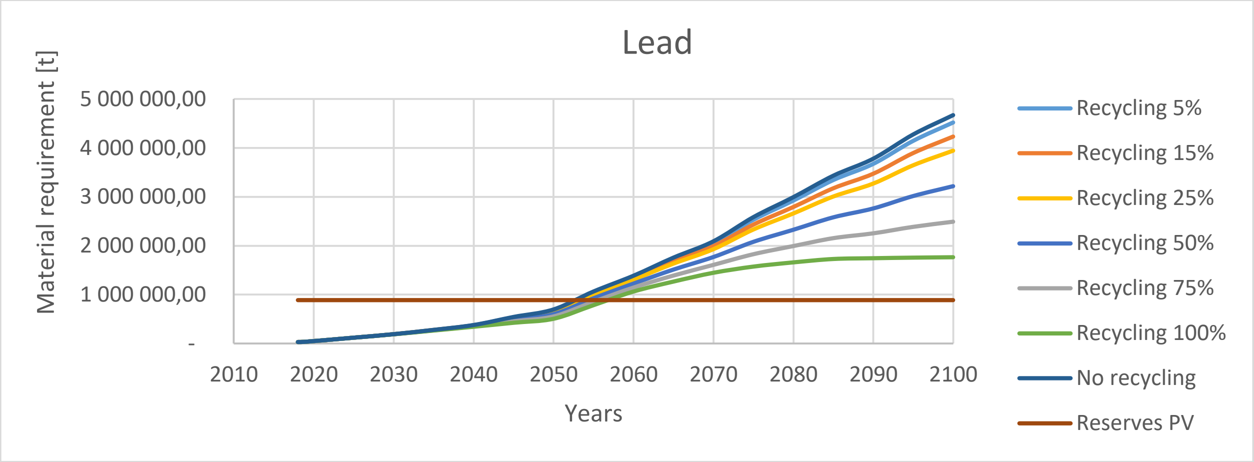

Figure 4.13. Recycling impact on Lead consumption for PV production (own work)

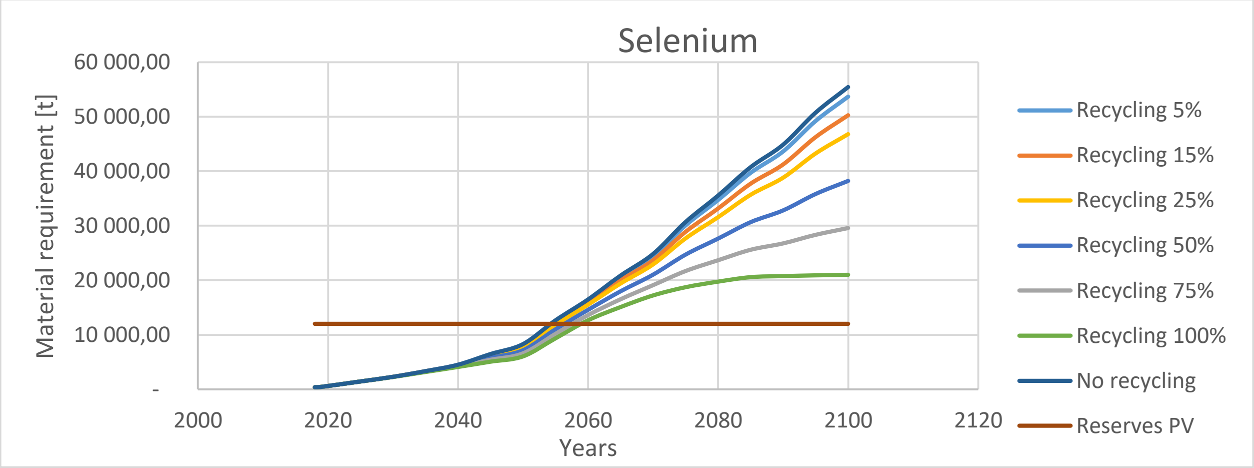

Figure 4.14. Recycling impact on Selenium consumption for PV production (own work)

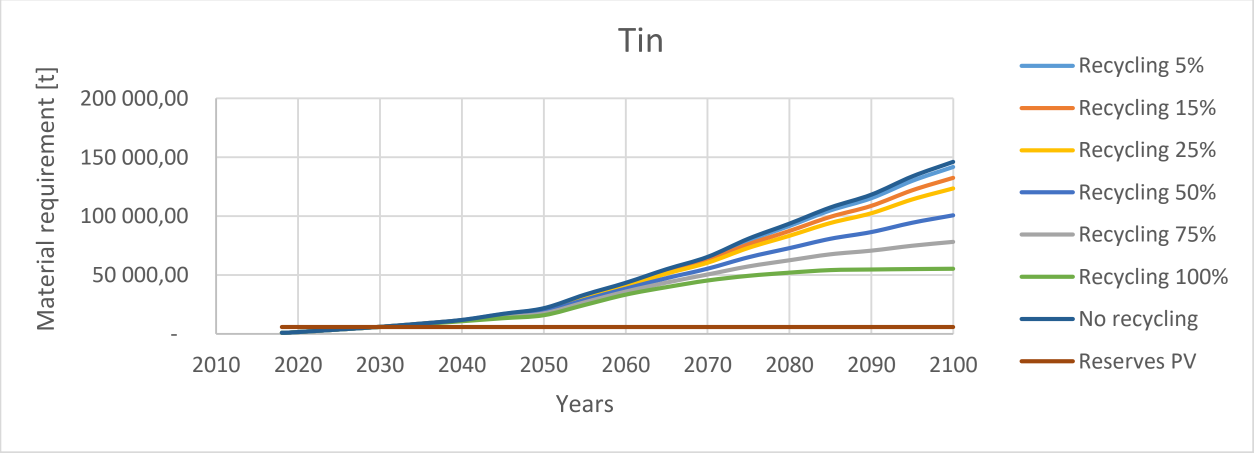

Figure 4.15. Recycling impact on Tin consumption for PV production (own work)

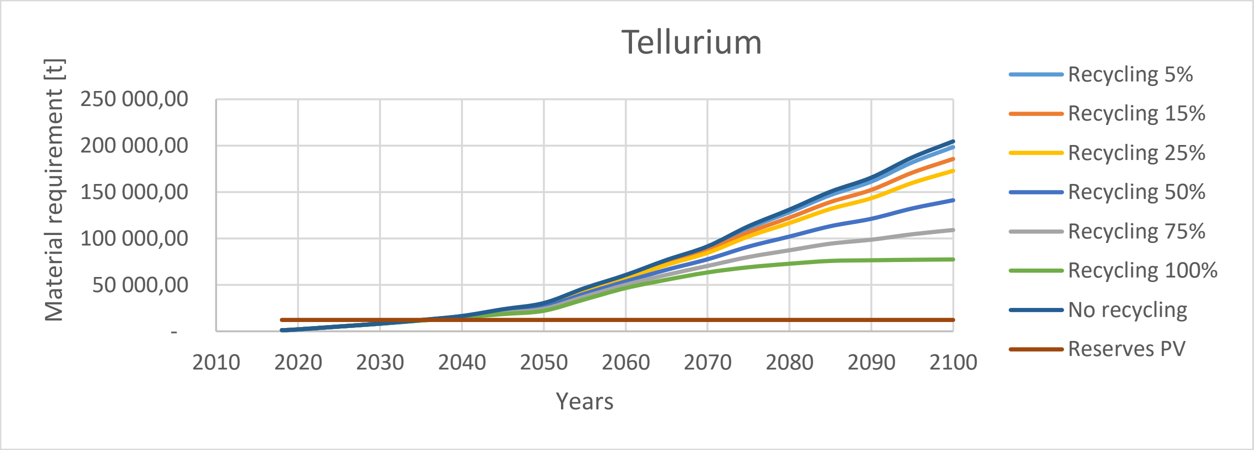

Figure 4.16. Recycling impact on Tellurium consumption for PV production (own work)

It can be seen that recycling of individual metals reduces the need for new materials. Unfortunately, in many cases, it is not sufficient to meet the needs with the reserves. Therefore, secondary materials would not be able to cover a whole material demand. However, end-of-life modules should be recycled to recover many valuable metals and to make the PV technology sustainable.

However, the results are only an estimation. In fact, they may vary depending on the adopted energy transition plan. Moreover, the error may occur due to the assumption that most of the available panels on the market are silicon panels. The share of thin-layer panels is expected to increase. The 3rd generation panels based on new technologies and materials will also be increasingly important, which are based on different materials. Photovoltaic technologies are constantly being developed in terms of efficiency and endurance, allow obtaining the same power with fewer modules. Therefore, the amount of materials required for the production would decrease. Extended lifetime of the modules extends would have a positive effect on the demand for materials. In addition, it is also worth adding that the recycling and recovery of damaged panels or defective or unused, which were not included in the installed capacity. Therefore, the amount of additional material would definitely increase. It is also worth adding that strategic elements are also used in other renewable technologies. Therefore, it is worth remembering about it, taking into account the security of supply.

4.5. Abiotic depletion

Finally, using the SimaPro software with Ecoinvent databases, the abiotic depletion parameter was calculated for each of the metals used in the production of photovoltaic panels. The CML methodology was implemented, which is often considered a complete methodology because it deals with different environmental impacts (Guinée et al., 2002).

The CML method was developed in 1992 by the Institute of Environmental Sciences of the University of Leiden and it is a midpoint-oriented methodology (Hischier et al., 2010). It is divided into two groups of impact categories such as obligatory impact categories (base line impact categories) and additional impact categories which may be used according to the study requirements.

Depletion of abiotic resources is one of the baseline impact category. It is related to the protection of human health and welfare, as well as ecosystem health. This impact category indicator describes the extraction of minerals and fossil fuels for further use in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals, clay, peat and fossil fuels and it is presented as kg of Antimony (Sb) equivalents per kg of extraction. It uses information about concentration reserves and rate of de-accumulation. It refers to the global scale (Van Oers and Guinée, 2016).

Abiotic Depletion Potential (ADP) is the characterisation factor. It is derived from each extraction of element and is a relative measure with the depletion of the reference element- Antimony in this case. Mass flow of an element (metal) is multiplied with the characterisation factor (ADP presented as kg of antimony equivalents/per kg used material, for instance, PV module). Abiotic Depletion Indicator (ADI) is obtained by multiplying mass flow of an element used with the characterisation factor. It is described by the following equation (Pikoń, 2012):

$$ADI = \sum_i ADP_i \times m_i \qquad \text{Eq. 4.3}$$

With

$$ADP_i = \frac{\frac{DR_i}{{R_i}^2}}{\frac{DR_{ref}}{{R_{ref}}^2}} \qquad \text{Eq. 4.4}$$

- ADP_i -Abiotic Depletion Potential of resource i (generally dimensionless)
- m_i -quantity of resource i extracted (kg)
- R_i -ultimate reserve of resource i (kg)
- DR_i-extraction rate of resource i ($kg \cdot yr^{-1}$)
- R_{ref}-ultimate reserve of the reference resource, antimony (kg)
- DR_{ref}-extraction rate of the reference resource, R_{ref} ($kg \cdot yr^{-1}$)

Table 4.13 contains the ADI indicators for the individual metals used in the production of silicon crystalline and thin-film PV modules.

Table 4.13. ADPs for metals in PV modules (own work based on Ecoinvent database)

Substance	Value	Unit
Silicon	1,40E-11	kg Sb eq
Aluminium	1,09E-09	kg Sb eq
Gallium	1,46E-07	kg Sb eq
Nickel	6,53E-05	kg Sb eq
Zinc	5,38E-04	kg Sb eq
Copper	1,37E-03	kg Sb eq
Lead	6,34E-03	kg Sb eq
Indium	6,89E-03	kg Sb eq
Tin	1,62E-02	kg Sb eq
Molybdenum	1,78E-02	kg Sb eq
Cadmium	1,57E-01	kg Sb eq
Selenium	1,94E-01	kg Sb eq
Silver	1,18E+00	kg Sb eq
Tellurium	4,07E+01	kg Sb eq

Then the ADP was calculated for each photovoltaic technology: c-Si, Cd-Te and CIGS/CIS modules, getting the results presented in figures 4.17-4.19.

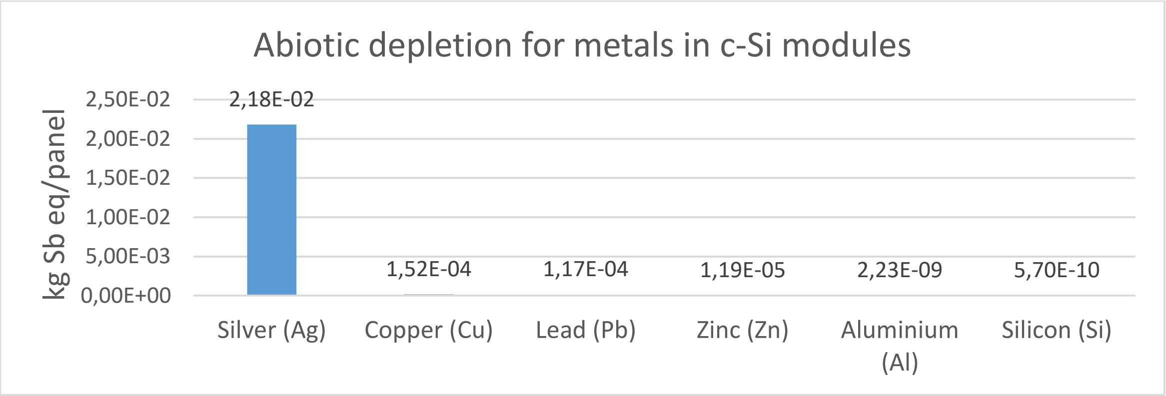

Figure 4.17. ADI for metals used in c-Si module production (own work based on Ecoinvent database)

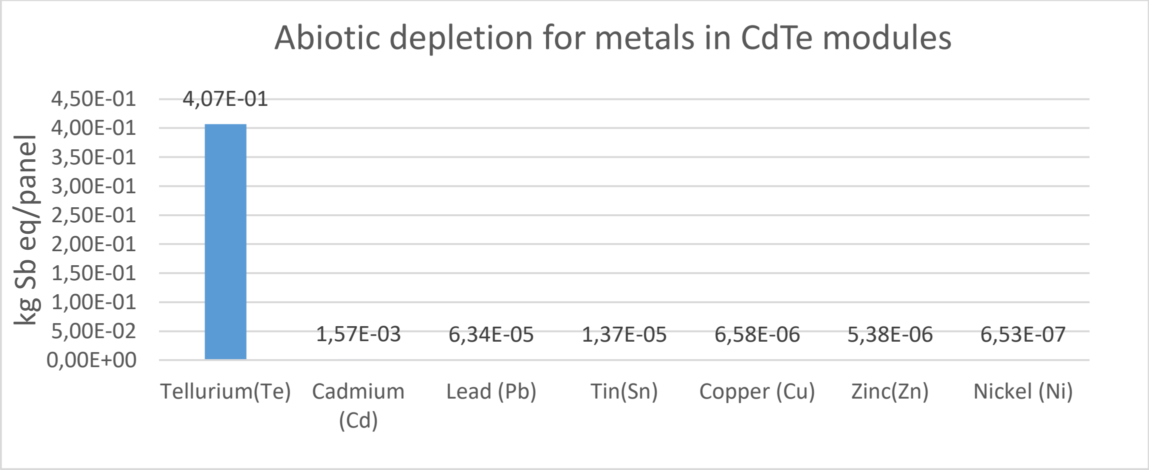

Figure 4.18. ADI for metals used in Cd-Te module production (own work based on Ecoinvent database)

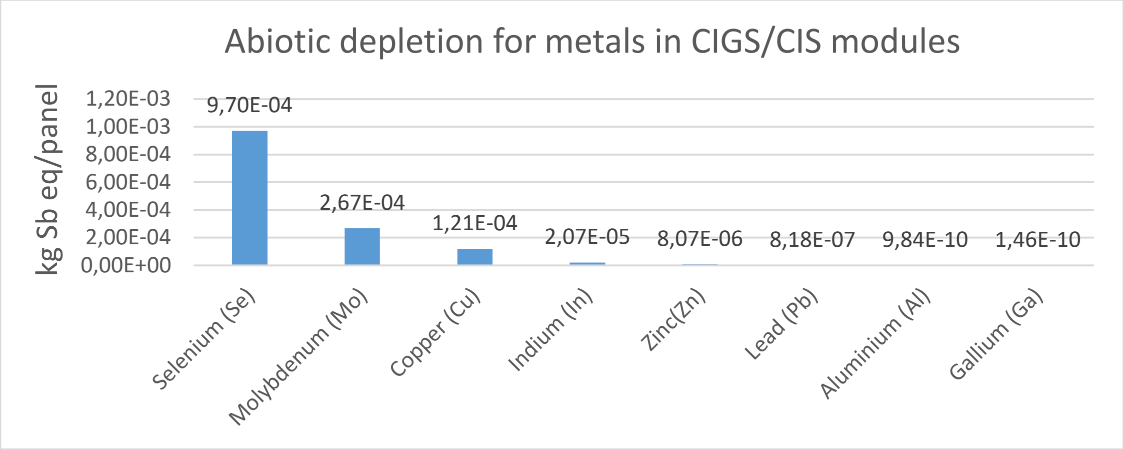

Figure 4.19. ADI for metals used in CIGS/CIS module production (own work based on Ecoinvent database)

It can be seen that the most depleting metals are silver, tellurium and selenium. Therefore, their level should be monitored carefully.

The reference substance is usually antimony (Sb), but the choice is arbitrary and does not matter in the final results. If a different reference was chosen, the relative sizes of the characterization factors would not change. Antimony is the first element in the alphabet and provides a complete set of necessary data related to the extraction rate and ultimate reserve, that is why it was chosen as a reference substance. It is important to define a reference substance, because it allows getting consistent indicator result for different substances, which can therefore be compared with each other (Van Oers and Guinée, 2016).

It is obvious that resource depletion is a serious issue. That is why the sustainable management of raw materials is important. It is known that you can manage what you can measure. Therefore, there is a need to monitor human impact and the consumption of individual minerals, starting from the national level. Unfortunately, it is difficult to determine the level of resource depletion and resource availability accurately. This parameter is defined as a function of the annual extraction rate and the geological reserve of the resource. Exact determination of the reserves is more problematic as by definition this parameter will never be available.

In the currently defined model, the ultimate reserve is considered to be the best estimate of the finally recoverable reserve and also the most stable parameter. Production and annual production rates are published and updated by the US Geological Survey (USGS) or the British Geological Survey (BGS). Consequently, the characteristic coefficients should also be updated regularly, but unfortunately, this is no longer done. Moreover, the development of a correct method is difficult because its empirical verification is impossible. That is why the abiotic depletion impact parameter is heavily debated (Van Oers at al., 2019). However, future resource availability for metals needs to consider recycling as well as any losses in the value chain.

5. Results discussion

Based on the results achieved in this work, it can be concluded that the switch to a low-carbon electricity mix would result in a higher demand for metals. What is more, photovoltaics makes a large contribution to this phenomenon. The analysis carried out in this dissertation delivered estimated dates of metal depletion intended for the production of photovoltaic modules. Therefore, ensuring a secure supply of metals seems to be a bottleneck in the value chain of the PV industry, as it was presented in this study. Metals that can run out the fastest are silver, tin, tellurium, cadmium, indium, lead and selenium. Consequently, the greatest attention should be focused on these materials when preparing strategies and production programmes. Furthermore, we must focus primarily on exploring the recovery possibilities of those metals whose reserves are the most doubtful.

The analysis in this paper focuses mainly on the last stage of the product life cycle, where analysis carried out in this paper focuses mainly on the last stage of the product life cycle, i.e. management of end-of-life panels. From a circular economy point of view, this may not be a complete picture, as value is lost at each stage of the value chain. Therefore, it would be worth extending the research to the earlier stages, i.e., production and design, which are very crucial in a circular economy concept. Also, the calculations of the materials' demand did not take into account the efficiency of individual production processes. Since it is known that this efficiency is not 100%, some materials are lost, so the demand will be greater. Despite this, it can be seen that recycling of panels even with 100% recycling rate will not significantly delay metal depletion. Nevertheless, it is a necessary practice that will allow to save large amounts of materials and, as a result, to produce new PV modules or other products.

In this work, the impact of PV implementation levels on the scale of metal production is quantified. To make it possible, a number of simplifications have been adopted. It was assumed that the share of individual technologies over a period of 100 years will be the same. In reality, this would change. As a consequence, the level of demand for individual metals will vary, therefore those metals, such as silver, which is a metal that is depleting very fast, probably would not be exploited as intensively as before. This is certainly a limitation of this paper. More generally, this dissertation highlights the possible limitations of the rate of increasing metal production for certain PV technologies and presents an approach to assessing projected demand for metal growth. The framework developed may be useful for the assessment of material consumption in particular technologies. It should also be remembered that the analysis did not take into account third-generation technologies that involve the consumption of new materials. As mentioned above, the level of their use will increase in the future.

During this investigation, one scenario for energy and power demand until 2050 presented by IRENA and one of the RCP2.6 scenario was examined. It has to be remembered that there are many different scenarios with many different factors and focusing on different aspects that could be adopted influencing the final results. While the forecasts up to 2050 may be very reasonable and in line with reality, forecasts after 2050 may be subjected to a greater uncertainty. This is due to the fact that the current regulations and energy targets are set until 2050. Thus, further obligations and scenarios will be developed in the coming years. They would evolve taking into account the current development progress and emerging problems, especially related to the global warming.

Most of the impact indicators in the LCA analysis may be measured and calculated using different methods. However, the final results may be different depending on the method. Different methods focus on different aspects, use different approaches, and rely on different databases, which are often out-of-date or take into account different elementary flows. Thus, the use of several methods is recommended in order to obtain a more global view of a problem.

In terms of abiotic depletion of resources, the choice of the method is quite complicated, because each method is based on a different definition of a depletion problem. They include different assumptions, such as: mining cost will be a limiting factor for resource depletion, collection of metals and other substances from low-grade ores are connected mainly with energy, scarcity of minerals is a major threat and mining and processing of mineral resources affect the environment, which is the main problem.

Considering different problem definitions, there are many methods of assessing resource depletion. Based on the experience, recommendations some methodologies for abiotic depletion of resources have been proposed. Midpoint methods that address this problem, apart from CML method (that has been adopted in this paper) include the EcoIndicator 99, EcoPoints 2006, EDIP 1997, EPS 2000, IMPACT 2002, ReCiPe method (Klinglmair et al. 2013). Therefore, implementation of different procedure that is based on resource reserves, exergy consumption, future consequences of resource extraction, willingness to pay the marginal cost of resource extraction and distance-to-target approach could provide us with slightly other results.

Nevertheless, it should be remembered that the current models do not take into account the recycling of metals and minerals. Such an approach may lead to the wrong conclusions regarding the availability of particular materials. The materials recovered in the recycling process can be treated as a supplement to the available resources and thus reduce the extraction of the primary resources. The recycling process, which has become more and more popular in recent years and maybe an indispensable practice in the future, entails the need for further improvement of resource depletion indicators modelling in an LCA from inventory stage up to impact assessment procedure.

The global COVID-19 pandemic disrupted global supply chains within all sectors, including metals, which are increasingly in demand due to the green and digital transition. Since Europe has the ambitions to strengthen its own position as a leader in sustainable development, it should draw the appropriate conclusions from recent events to ensure a safe supply of metals. This is because the metal sector is a key player in the transition to a new digital and renewable economy. European Metals Association (Eurometaux) that brings together companies from the metal industry has prepared a special program for the EU that will contribute to the development of investments, and it encourages to take bold steps in order to make the European metals sustainable.

The transformation path of the European economy into a climate-neutral one requires access to a number of metals (base, precious and specialty), which are presented in figure 5.1 below.

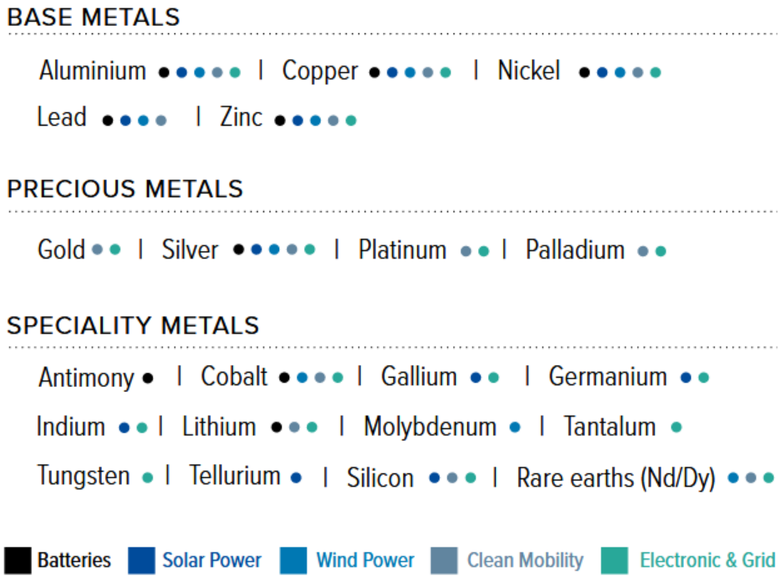

Figure 5.1. Metals required in green and digital technologies (EUROMETAUX, 2020)

We can see that metals used in the production of the PV modules, such as silver or lead, are also consumed by other green technologies. According to the World Bank (Hund et al., 2020) the demand for such metals that are the basis for renewable and digital technologies will increase up to 500% for the renewable technologies, batteries and clean mobility. Figure 5.2 shows the present and future demand for metals in clean technologies and figure 5.3 presents the consumption of metals by individual technologies (EUROMETAUX, 2020).

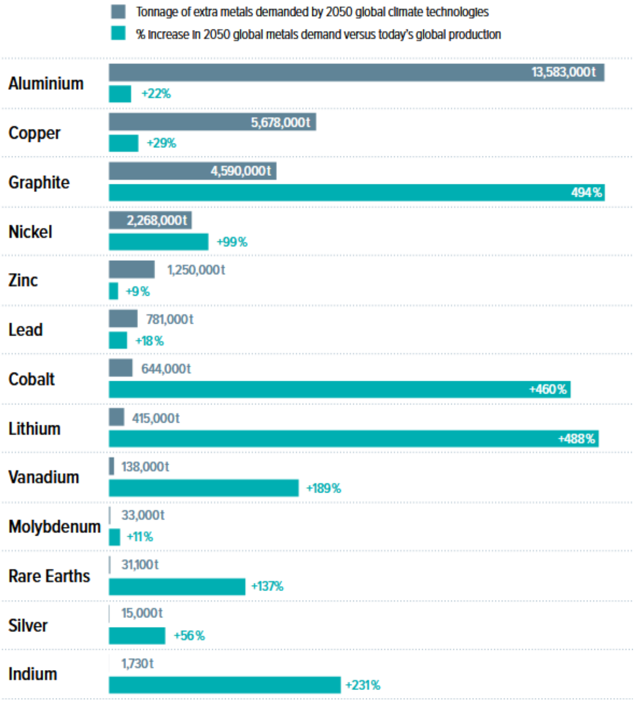

Figure 5.2. Present and future metals demand in green and digital technologies (EUROMETAUX, 2020)

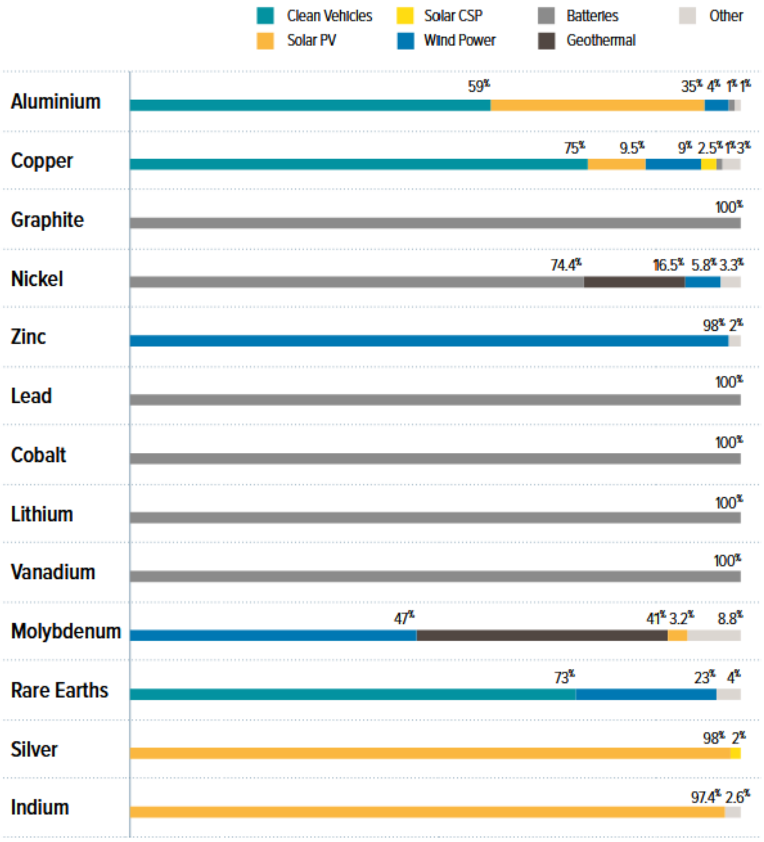

Figure 5.3. Consumption of metals by green and digital technologies (EUROMETAUX, 2020)

It can be seen that the photovoltaic industry is a greater consumer of silver and indium. The batteries, which are indispensable components of the systems based on renewable energy sources, require huge amounts of graphite, lead, cobalt, lithium and vanadium. Figure 5.2 shows that there will be an extra demand for such materials by 2050, in connection with ambitious plans regarding the energy transition and the expansion of green, digital technologies in other sectors.

In this study, individual metal reserves are based on current estimates of metal uses for specific applications. Note that future demand for non-PV applications may change, therefore, accordingly, reserves for cell manufacturing purposes may increase or decrease, which will be reflected in the results of the depletion year. Therefore, interactions with other industries that require the same materials as PV industry must be considered in order to comprehensively assess constraints caused by the availability of materials for growing PV market share. The photovoltaic industry for some of the analysed metals represents only a fraction of current production. However, for some of them, it is a major consumer. Hence, it can be concluded that the increased demand will result in increased competition and rivalry between different industries. This competition from other industries should not be neglected but carefully observed (Davidsson and Höök, 2017).

It is important to remember that Europe has limited industrial capacities for critical metals such as lithium, cobalt and rare earth metals. Therefore, it is essential to implement appropriate strategies in order to prevent a further decline in metal production in Europe and to stimulate new investment that would increase mining, smelting and refining, production, processing and recycling capacities.

It should be noted that the European metal sector has a high global environmental performance and metals coming from European companies can guarantee world-class sustainability of new renewable technologies as this sector is a leader in implementing the circular economy practices (EUROMETAUX, 2020).

Metal companies show interest in investments that will improve the environmental performance of smelting, refining and production operations. Moreover, measures are being taken to increase the sustainable mining opportunities of base and critical metals in Europe and abroad. More and more metals are recovered from batteries, electronics, transport, packaging, buildings and other waste streams, ensuring a small impact on the environment and human health.

Legal and political support, as well as the creation of appropriate tools, are crucial for the implementation of all actions that will support the development and expansion of all stages of the European metal value chains, which are shown in figure 5.4 below.

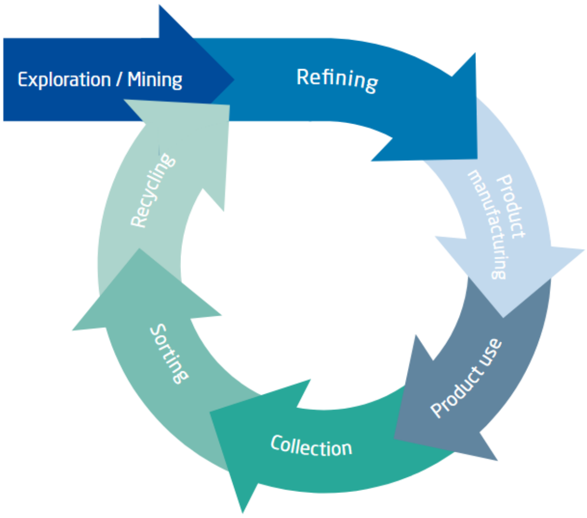

Figure 5.4. The EU Metals Value Chain

This is important as it is a key strategic element of the green and digital transformation, which should be legally confirmed. To make new investments, European metal companies will need a consistent regulatory framework at EU and national level that will allow competing with other regions of the world.

Clean energy technologies are more mineral-intensive than those based on fossil fuels. An electric car requires five times more minerals than a car with the fuel-based engine (figure 5.5). On the other hand, an onshore wind farm uses eight times more materials than a gas-fired power plant with corresponding capacity, which can be seen in figure 5.6.

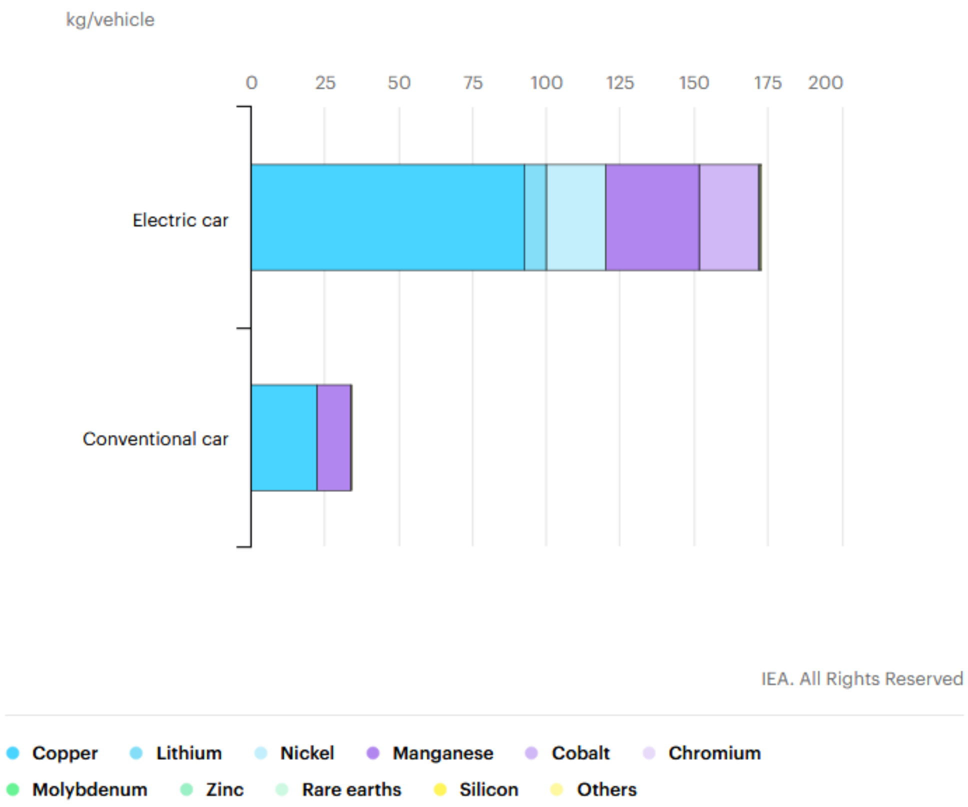

Figure 5.5. Minerals used in selected transport technologies(IEA, 2020)

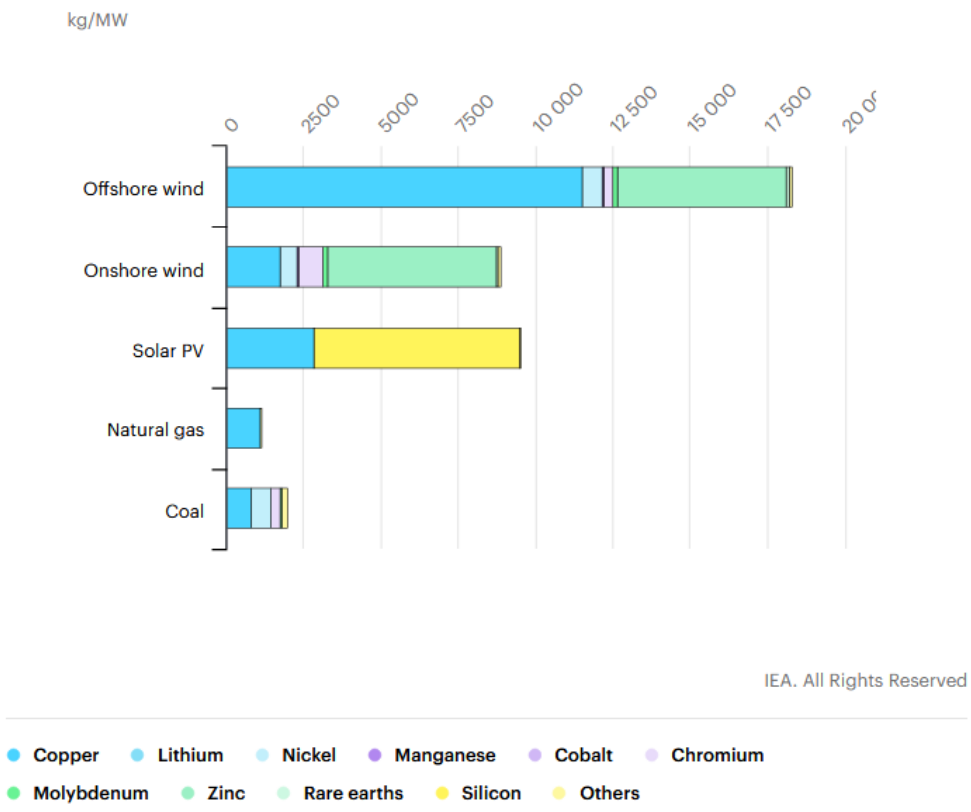

Figure 5.6. Minerals used in selected power generation technologies (IEA, 2020)

Even clean coal technologies or another fossil fuels-based solution, but with higher efficiency and consequently lower emissions, use much larger amounts of minerals than standard technologies. For example, the most efficient coal-fired power plant consumes higher amounts of nickel in order to provide higher combustion temperatures in comparison with the least efficient ones. Hence, the transition to green and low-carbon technologies will drive the growth in demand for minerals. For some of them, it is a major demand driving force, as in the case of lithium. The largest amounts of this metal are currently used for electric transport and energy storage, which stand for 35% of today's total lithium demand (IEA, 2020a).

According to a life-cycle analysis prepared by UNEP in the Green Energy Choices Report (UNEP, 2016) PV electricity requires a greater supply of metals, especially copper and aluminium, what it is shown in figure 5.7.

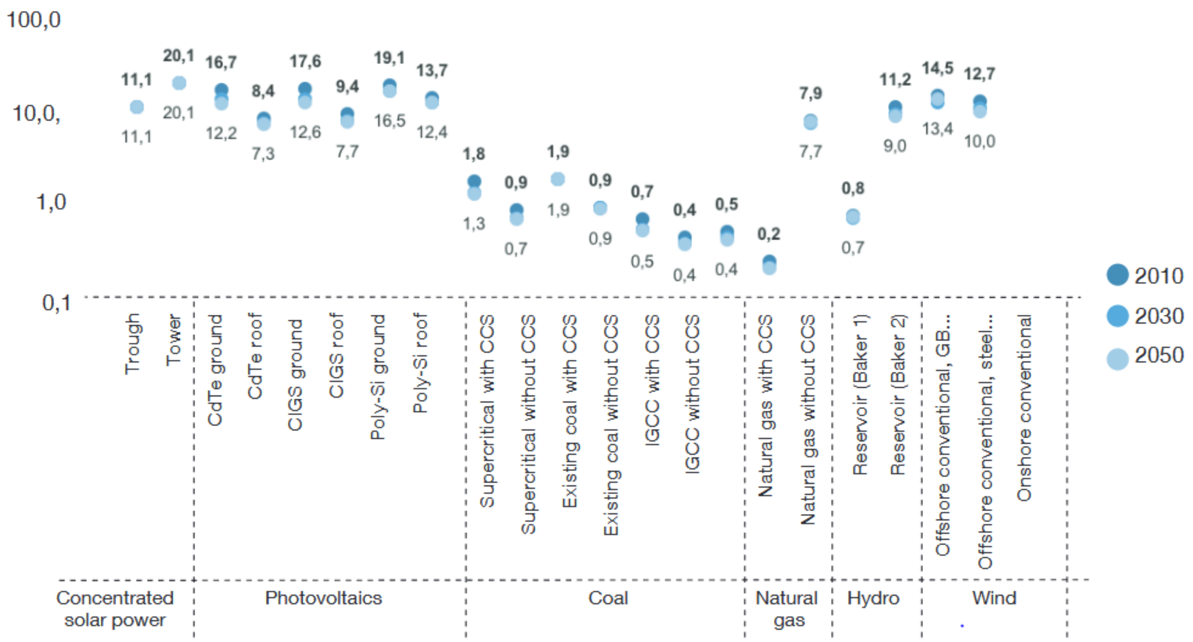

Figure 5.7. Comparison of the impact on metal depletion, in g Fe eq., of different technology sources, for 1 kWh in Europe (UNEP, 2016)

However, PV technologies show clear environmental benefits in terms of climate change, particulates, ecotoxicity, human health and eutrophication comparing to fossil fuel technologies. What is more, the environmental and human health advantages come from end-of-life panels recycling. Figure 5.8 below shows that recycling of silicon- crystalline modules, which was carried out in a recycling facility belonging to the group Deutsche Solar AG brings benefits in each impact category.

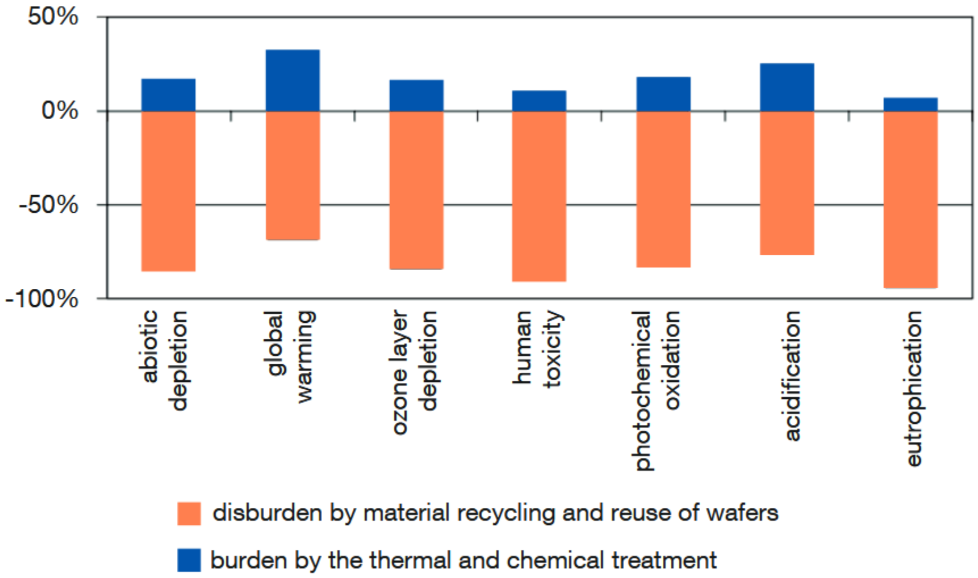

Figure 5.8. Life cycle environmental burdens and disburdens by silicon PV recycling by Deutsche Solar AG (UNEP, 2016)

It is predicted that in future Poly-Si, CdTe and CIGS technologies will likely reduce impacts and metal demand that will be a consequence of material efficiency improvement and increased power generation efficiency. For now, silicon-based technologies have a lower environmental impact than silicon modules, because they require more energy for the production phase and cause higher direct emissions when producing metallurgical grade silicon, polycrystalline silicon wafers and modules. What is more, the greatest amounts of metals are consumed by inverters, transformers, cabling, assembly and construction. However, metals used for such applications may be easily recovered in the recycling process.

Figure 5.9 presents the life cycle climate change impact from the production of 1kWh of electricity from different technologies in 2010.

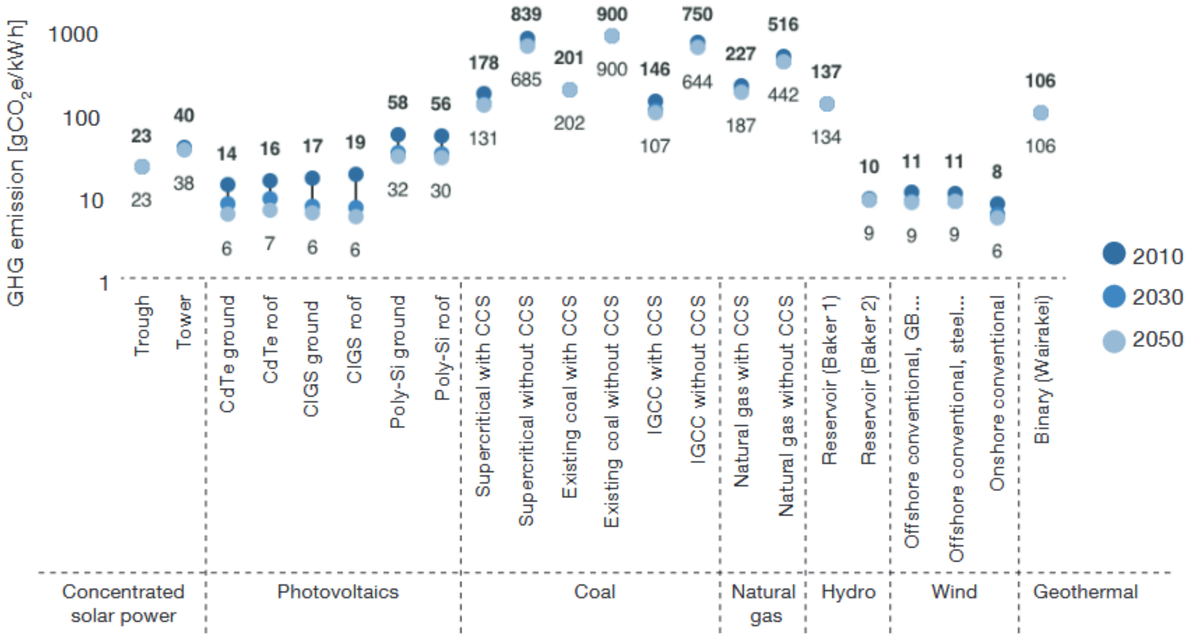

Figure 5.9. Comparison of the GHG emissions of different electricity supply technologies, modelled for 1 kWh produced in Europe (UNEP, 2016)

It is visible that the coal power plant is responsible for the highest global warming effect (~900 g/kWh), followed by natural gas. Thus, the fuel combustion in a power plant is still the main source of greenhouse gas emissions, even for carbon capture and storage (CCS), assuming a gas stream capture efficiency of 90%, because an additional energy is required to carry out the capture, transport and injection of CO_2. Technologies based on renewable energy sources are characterised by much lower emissions. It is visible that the future greenhouse gas emissions will be reduced as a result of technological development.

6. Conclusions

The thesis objective is to examine the material flows within the PV industry and the recovery potential of valuable fractions through recycling, highlighting the strengths and weaknesses of the transition to a circular economy. It focuses on determining the demand for materials for the production of photovoltaic modules that should be implemented to cover the demand for solar electricity until 2100.

The main conclusions that emerge from this work are:

1. The energy transformation that is associated with the switch to a low-carbon electricity mix would result in great demand for materials.

The further development of economies and the increase in the use of technology that produces energy from renewable sources, such as photovoltaics contribute to an increase in the demand for certain materials such as silicon, tellurium, gallium, indium, selenium, silicon and glass. Moreover, there will be increased demand for structural materials such as concrete, steel and aluminium as well as copper for wires and cables, which are part of the BoS.

2. Photovoltaics will be a leader among renewable technologies, its share will increase and thus the demand for specific materials that are limited, as it was presented in chapter 2.

It is hard to say whether the availability of materials may limit the development of photovoltaics. However, ensuring this amount of raw materials will be a big challenge, considering the technologies available on the market, i.e. silicon and thin-film panels. It is, therefore, necessary to update the material flows going within the PV industry, taking into account new possible technological solutions and technological development in terms of material efficiency, because the situation is changing dynamically. It is a very crucial information. Some metals can be easily replaced, but some metals have no substitutes. Therefore, it is worth considering this aspect when production relies on access to specific metals

It should also be remembered that if the global deployment of photovoltaics technology grows rapidly, the required materials for the production of the modules must be delivered at an increasing pace. And as it is known, the mining possibilities are limited. Therefore, despite the fact that the reserves of metals may be sufficient, we may not be able to extract them on time. That is why recycling should be taken seriously as it can provide large amounts of additional resources.

3. In the coming years, the photovoltaic market will be dominated mainly by 1st and 2nd generation technologies, although new technologies will strengthen their position, as it has been discussed in chapter 2.

Assuming that most of the projected power would be supplied by silicon modules, significant amounts of silicon and silver would be needed. It is known that the consumption of silver in the PV industry accounts for a large part of the production of this metal. Therefore, competition with other applications may be critical in terms of future availability and cost because silver largely determines the price of the

PV module. If silver would be eliminated from use and the consumption of silicon would decrease, it had probably positively affected the further development of photovoltaics.

4. Thin-film modules, which are the representatives of the 2nd generation of photovoltaic technology, are less material-consuming than silicon panels, according to the material analysis in chapter 4.

This technology uses a small amount of material as the semiconductor layers are less than 1µm thick. However, these PV modules are less efficient, therefore require more space than the first-generation panels in order to deliver the same power, thus also extra materials. If thin-film modules dominated the photovoltaic market, there would be a problem with access to rare elements. The most common technologies commercialised today such as CIGS and CdTe, require significant amounts of indium, gallium, selenium, cadmium and tellurium. It seems that the availability of these materials, especially indium and tellurium, will be a challenge given the development rate of photovoltaic technology. When forecasting future development paths of this industry, the potential improvement in material consumption and the availability of secondary resources should be taken into account.

We have to be aware that the further development of photovoltaics will require access to various materials. Technological choices and material intensity improvements will determine the exact amount of each material.

5. Material challenge is a crucial issue and may act as a real bottleneck in terms of PV production and a green transition (taking into account the results presented in chapter 4.

Comparing the forecasted demand for specific materials and the data on reserves, the most depleted metals that may disrupt the production of new devices were calculated. Metals that can run out the fastest are silver, tin, tellurium, cadmium, indium, lead and selenium. Therefore, research and development in terms of recovery and substitution possibilities of these metals should be considered as a priority.

The worst situation is for silver, which plays a vital role in silicon crystalline PV cell. According to the analysis, its reserves for photovoltaics in 2020 have already run out. Silver powder in the form of a paste, thanks to its excellent reflective and conductive properties, collects and induces electrons that have been excited by the photoelectric effect. In this way, electricity is generated which may be consumed immediately or stored in a battery. Manufacturers introduce a practice called "thrifting". It is a process about reducing the amount of silver used in PV cell. The main reason is the high price of this metal, which also reflects its diminishing availability. Since the silver price is going to rise from 2020 up to 2024, the rate of thrifting it is going to reduce (Bellini, 2020). According to the Report of the Silver Institute, the amount of silver consumed for PV production may significantly decrease between 2016 and 2028, from 130 mg to 65 mg per cell. Change of the silver content may affect the efficiency of the panel. However, even with such reduction, the cell output is predicted to increase from 4,7 W to 6 W per cell by 2030. It is a consequence of technological advancements, modern design and optimisation of the manufacturing process (Turner, 2019). However, the amount of silver cannot be reduced indefinitely. There is a point where the losses will outweigh the benefits of using cheaper substitutes such as copper or aluminium. However, silver has the lowest electrical resistance among metals. Therefore, in terms of energy efficiency, it is unbeatable. Hence, it is possible to generate some savings while choosing cheaper materials. Nevertheless, an increased number of modules will be needed to match the capacity. However, substituting silver with copper presents a number of challenges. Most of all, copper reduces the lifetime of silicon solar PV cells. This is due to the diffusion of copper into silicon where it traps the charge carriers in the semiconductor material, so a diffusion barrier is required. In addition, copper oxidises into a porous compound on exposure to air. In order to solve this problem, additional protection of the electrode contact should be implemented. Additionally, embedding copper in the cell is a more complicated process, some more steps are required than in the case of silver paste (Appleyard, 2012). Therefore, the introduction of copper into the production of silicon solar PV cells will therefore increase the complexity of the process, which is associated with an increase of the production cost. Additional costs will also be associated with the R&D and new equipment to adapt copper or aluminium as the substituted metal. What is more, they are less reliable. Thus, it is not predicted that they would gain significant market share until 2030 as the other, more efficient technologies are available (CRU, 2018). Thin-film alternatives seem to be a good solution, which offers a variety of advantages in terms of weight, cost and flexibility and could emerge as the key solution threatening silver. However, they have lower efficiency levels, but they are constantly being improved, and one day they may become very competitive.

In terms of thin-film modules, there are concerns about the availability of indium, cadmium, tellurium which have a really low crustal abundance. However, there are some alternative solutions that are based on more abundant elements such as Cu, Zn, Sn, and sulphur, for example, copper zinc tin sulfide (CZTS) module. It has gained interest, because it offers favourable optical and electronic properties, similar to CIGS module. However, unlike the most popular, conquering the market thin-film modules (CIGS, CdTe), the CTDS panel is made of abundant and non-toxic elements. The increased material price and availability of tellurium and indium, as well as the toxicity of cadmium, have motivated scientists to look for some alternatives. Thus, CZTS cells can contribute to reducing material bottlenecks that occur in CIGS and CdTe. CZTS is similar to the structure of CIGS chalcopyrite, but is based on the available metals. The price is about five times lower than for those used in CIGS, and estimates of their global reserves (for Cu, Sn, Zn and S) suggest that by using them it is possible to produce enough energy to power the world consuming just 0.1% of the available raw material resources. Moreover, CZTS is non-toxic. The prices of indium and tellurium are increasing rapidly because liquid crystal display industries highly consume them. Due to the toxicity of Cd and Se and availability issues of In and Te, the production of the photovoltaic devices based on these absorber layers is limited. CZTS cells can reach the efficiency of 12,6% (Jhuma et al., 2019). Therefore, CZTS-based thin-film photovoltaic cells are one of the promising representatives of the future thin-film photovoltaics. The cost of producing thin-film photovoltaic technology based on CZTS is very low compared to other types of photovoltaic devices. Therefore, there is a reason that they can be used on a larger scale. Its high efficiency, availability, low price, ease of manufacture and adequate stability, along with further development, are expected to constitute a new generation of thin-film PV technology. (Gao et al., 2017).

6. The number of end-of-life panels will increase, and it will be necessary to implement recycling and recovery strategies, as well as infrastructure and processes that will be supported by the introduction of appropriate legal regulations and financial supplements, encouraging reprocessing and safe disposal of waste, as it was investigated in chapter 3 and 4.

It will be necessary to introduce appropriate strategies and policies supporting the increase of the material intensity of currently available technologies, as well as the creation of conditions and infrastructure for material recycling and recovery. The introduction of such practices, which are promoted by the circular economy, will be crucial and necessary to achieve a more sustainable and resource-efficient renewable energy system in the future.

A clear legal framework will need to be adopted to support the recycling of photovoltaic modules. So far, the EU is a pioneer in this regard. In other locations, in the United States, Australia and Asia, the disposal of solar PV panels is not specifically regulated, which means that most of the end of life modules may end up in landfills. However, it should be remembered that recycling is the most sustainable solution, not only in terms of environmental and social impacts but also in terms of resources and economic efficiency. Recovered materials can be used to manufacture new solar PV panels or be sold on global commodity markets, thereby increasing the security of future raw material supplies.

7. Materials recovered from photovoltaic waste have great potential and can be reused as secondary materials to produce new modules or other products.

Table 6.1 presents material savings from recycling of end-of-life PV modules, taking into account the 85% recovery rate according to the EU's Waste Electrical and Electronic Equipment (WEEE) Directive (DIRECTIVE 2012/19/EU).

Table 6.1. Material savings and modules production from secondary materials (own work)

	Material savings [t]	**Modules**	**Power [MW]**
Total		16 208 205	4 792.29
c-Si	278 368 009.67	15 046 919	4 664.55
Thin film	14 650 947.88	1161286	127.74
CdTe	4 395 284.36	366 273	40.29
CIGS	10 255 663.51	795 012	87.45

It can be seen that recovered materials from end-of-life PV modules by 2100 would be sufficient to produce more than 16 million new PV modules. It is the amount that could provide a power capacity of 4.8 GW. It is twice as much as the currently installed PV capacity in Poland. Therefore the potential captured in secondary materials coming from end-of life modules is huge and should not be wasted.

8. A circular economy is essential for the PV industry to be sustainable. Appropriate practices should be introduced, starting with the product design, as stated in chapter 2 and 3.

Circular thinking should be the basis of the PV sector. Eco-design towards designing out waste and pollution, designing in repair, reuse and recycling is necessary. For this, more accurate estimates, calculations and analysis are necessary, which will take into account all industries using specific elements. It is important to find ways how to minimise losses and wastes starting from the early stages of PV module manufacturing process, eliminate substances of concern, extend the lifespan of solar PV modules, use materials and energy in a more effective way and incorporate recycled content in order to retain value as long as possible. This should be a priority.

It is crucial to determine how products should be designed for modularity, upgrades, repairs or deconstruction. The manufacturers, who are involved in the design process of their product, should keep in mind the future management of waste components from PV modules so that they could be easily repaired, recycled and reused. What is more, they should design their products and optimise all stages of the production line and material delivery in such a way to reduce the negative impact on the environment, by lowering the excessive energy and water consumption. It is also important to look for opportunities how to give a second life to products as in case of batteries from vehicles, which may be used as solar PV storage for houses and schools, and in this way decrease household electricity bills by up to 30% (NREL, 2020).

9. Recycled metals will not meet the demand for new modules, but they will be an important alternative to primary resources that will be essential in the future, considering the results shown in chapter 4.

It can be seen that recycling of end-of-life modules does not play a big role until 2100. Recycled materials could cover a relatively small part of the expected material requirements. Nevertheless, recycling of the end-of-life modules is necessary to make this technology sustainable and non-dependent on primary materials supplies.

10. Recycling of end-of-life modules has many environmental, social and economic benefits, but it needs more research and development to be a fully viable technology, as presented in chapter 3.

Recycling of PV modules is a relatively new technology; therefore it is still a laborious and quite complicated process. Depending on the recycling method, it includes mechanical, chemical and thermal treatment of waste. In addition, the recycling technology must be adapted to the specific module production process. At present, it is difficult to find profitable business models for recycling. This is due, among other things, to the fact that currently, the number of modules to be recycled is low, which makes the process unsustainable. PV modules are relatively new products; the first installations have not reached yet the end stage of their lifetime. Therefore, recycled panels today are those that are out of service because of the failures. However, these volumes will be much larger in 10 years, and then an efficient system for collecting, sorting, separating, cleaning, recycling modules and recovering metals will be necessary. We need more advanced technologies for metal recycling and recovery. Although some steps have already been taken and the recovery rate of some fractions reaches results above 90%, there is still a technology gap that should bring together economic, environmental and common-sense results. To push the solar PV industry closer to a circular economy research effort must be concentrated. In particular, on silicon recovery, which accounts for about half the cost of the module, and after removing the aluminium frames and glass covers, it accounts for most of the PV waste. The purity of silicon is also important, as it decreases as a result of recycling. Moreover, the silicon that is used in new modules is much cleaner than in modules from the past. Therefore, the priority for PV recycling is to find ways to improve the purity of the recovered silicon in an economical manner. It may require different processes than purifying virgin silicon, so it is crucial to determine what is needed. It is important to consider the recycling of other materials as well and to develop technologies that will allow for profitable recovery of even small amounts of metal such as silver, tin or lead. For this reason, more research is required to explore the most cost-effective ways to recover potentially valuable materials and neutralise hazardous materials such as lead.

Changes in the construction of PV modules and technological development have already made it difficult to recycle or reuse products from the past. Therefore, it will be important to follow further changes and monitor technological progress. Infrastructure investments must take into account and adapt to changes taking place in a dynamically developing PV sector, which implies a changing input stream to the recycling processes, which may require the use of various technologies and methods. Therefore, a robust research program is essential for the PV sector to achieve efficient, cost-effective and fully integrated recycling to recover and reuse valuable fractions. Detailed technical and economic analysis, life cycle assessments, material flows in the PV sector will be necessary for the development of strategies and business models that take into account the reduction of recycling costs, environmental impact, while maximising material recovery.

The process of obtaining primary metals, which are essential for renewables, has a negative impact on the environment. After the metal is mined, it is refined, processed and then transported to the producer, where it undergoes subsequent appropriate processes in order to be turned into desired products. All these processes are very energy-intensive and cause emissions to the atmosphere. Therefore, it is worth using recycling, which apart from reducing the demand for primary minerals, also solves all mentioned problems, and it is more economically viable.

Obtaining a kilogram of recycled metal requires much less energy. For example, the energy savings from using recycled metals are up to 92 % for aluminium and about 90 % for copper (Basu, 2015). Moreover, such a process reduces the exploitation of low-grade ores, which is a more energy-consuming process. However, in the future with technology development, it will become necessary to prevent shortages of some commonly used precious metals. In theory, metals can be recycled almost indefinitely without altering their properties, providing a valuable opportunity to reduce environmental degradation, energy and water consumption and contribute to the transition to a low-carbon, resource-efficient green economy. However, sometimes the recovery of metals in the recycling process is difficult due to the complexity of the products, which also translates into increased costs, so it is worth paying attention to the proper design of products. Although the mineral consumption for renewable energy technologies is much higher than in the case of classic energy solutions, the scale of greenhouse gas emissions related with their activity is a fraction of the scale of fossil fuel power plants. Emissions from the production and operation of renewable energy sources and storage technologies account for only 6% of coal and gas production (Markoglou and Murphy-McGreevey, 2020).

Another big challenge is to provide energy storage for unstable energy technologies, whose operation depends on weather conditions. According to the report of the European Commission, in order to integrate renewable sources with the grid in the EU, it will be necessary to develop and create innovative, economically profitable solutions in the field of energy storage. The development of storage technology will play an important role in achieving the 2050 decarbonisation goals, promoted in the European Green Deal and Paris Agreement while providing Europe's secure supply of energy (EC, 2020). The shift from conventional energy based on fossil fuels to new renewable technologies brings new opportunities but is also associated with an increased need and interest for energy storage solutions, followed by higher demand for various minerals, such as lithium, nickel, cobalt, graphite, manganese, aluminum, vanadium, rare earth metal and other alternative materials required for the production of batteries. Therefore, when considering the security of supply of materials for the production of photovoltaic modules, and other renewable technologies, the materials for the production of energy storage should also be included.

This thesis has several limitations, which result mainly from the simplifications adopted for the analysis. Knowing them may be useful in developing further, more detailed investigations. However, it may be treated as a reference point. Further studies should be developed taking into account new generations of PV technologies, and their changing market share, which will directly translate into the difference in demand for the appropriate types of materials and metals in the long term. In order to get a full picture of the material intensity of technologies supporting green and digital transformation, it would also be necessary to carry out a similar analysis for other technologies, such as wind farms or batteries. This study also does not consider the impact of the costs of both the extraction and acquisition of materials, as well as the costs of recycling and recovery, which is quite important for determining the profitability of such projects. Therefore, future works could be extended by financial analysis. It will be quite a challenge as the situation changes rapidly. Metal prices fluctuate under the influence of various factors, as do the costs of recycling as technology develops. Moreover, it would also be interesting to compare the demand for materials in the production of renewable sources based on different scenarios for energy and power demand projections. To be more precise, it is also recommended to take into account the material used for the production of the entire BoS system in order to estimate the material intensity of the entire PV installation, not just the module. It is also worth combining material analysis with LCA. The benefits of recycling are not only material savings, but also energy, water savings and reduction of greenhouse gas emissions. Showing the impact of implementing a circular economy that aims to optimise and balance the entire value chain could effectively encourage policymakers and manufacturers to implement such practices. Life Cycle Assessments and Environmental Analysis are essential tools to achieve sustainability during energy transition and implementation of the circular economy. They help to quantify and understand the real impacts on the environment, society and the economy, as well as identify the opportunities for development based on available resources and nature's ability to absorb pollutants. These tools use material flow analysis, input data analysis and systems thinking to provide solutions and strategies in production and consumption systems that aim to minimise the environmental footprint. Such targets will include new technologies, solutions and behaviours in various sectors, among others energy, metal production, transport, waste management and recycling. Therefore, the material analysis carried out in this thesis is an important element that may be useful in developing strategies and decision-making processes, and there will be many of them, as the energy sector faces many challenges in the era of transformation and decarbonisation (Davidsson and Höök, 2017).

To sum up, it is certain that the era of "take, make, and dispose" is coming to an end. This model of the economy is becoming inefficient, and the scarcity of resources makes it impossible to maintain. To accelerate the transformation of the energy system to the new circular model, funds are allocated to research centres such as the National Renewable Energy Laboratory (NREL), where work on materials for renewable technologies is underway (NREL, 2020). Scientists develop and design a material with the reduction, reuse and upcycling in mind. This is one of the key research area and the main part of the energy transition. It is known that we will need adaptive materials for energy systems. At NREL, on the basis of natural systems, solutions are sought to develop energy technologies that will be cheaper, lighter, more flexible, more durable and better adapted to the environment, and which will not exploit excessively the limited resources of the Earth. Therefore, a revolution has begun. Shifting to a circular economy will be a great challenge, but it is critical for a sustainable future. This will require a big change in the traditional approach to the market, customers and natural resources. However, with the support of policymakers, that may boost the transition by rethinking incentives, favourable policies and access to financing, it may be a dream that comes true.

Initially, the idea for this thesis was to develop the material flow and resource depletion in renewable energy area. However, this is a broad topic, therefore photovoltaics is a good start. In the future, it would be interesting to expand the work to other renewable technologies. It would start with batteries, which are an indispensable element of renewable energy system, including photovoltaics. In addition, another important step in the research would be a LCA analysis. So far, only abiotic depletion category has been tested, as a the most important representing of the materials and resources depletion. However, LCA allows for a more complex assessment of the environmental impact, due to its multi-aspect nature and versatility (Samson-Bręk et al., 2019). The use of LCA in the assessment of the waste management system is necessary to determine the real impact of various solutions on the environment, consequently, to select the least burdensome strategy. It is obvious that all manufactured products or provided services have an impact on the environment and the recycling processes as well. Both side of the analysis should be take into account, not only the pluses but also minuses of the recycling. At present, it is desirable to to minimize the impact of a product or service on the environment in all lifetime's stages. Such an approach, apart from environmental profits, may also lead to a reduction of production costs, which may improve the competitiveness of a given solution. The life cycle assessment refers to a model system that consists of interconnected processes that are responsible for specific functions. These processes consist of a set of material and energy flows between unit processes. Therefore, it is necessary to collect data on energy, chemical substances or raw material consumed and waste and emissions generated at each stage of the life cycle of a given product to perform analysis, including recycling processes, which are presented as an environmental friendly.

The circular economy supports creating value for the economy, society and business while minimising resource use and environmental impacts trough reducing, reusing and recycling. LCA is used as a measurement technique of the environmental impacts of products, services and business models. If we combine the robustness of the LCA methodology with the inspirational principles of CE we may obtain the holistic approach for sustainable innovation (Peña et al., 2020). The concept of CE should be based on the LCA. They allow measuring environmental performance, compare circular strategies and ensure a positive environmental balance from the design of new circular products and a broader picture of the project. It may be useful for CE decision-makers to assess trade-offs of impacts on a variety of environmental impact indicators. It is proven by Soledad (2015) that "to evaluate the impacts of the circular economy, applying a life cycle approach is highly beneficial. LCA can strengthen the propositions of circular economy, and the other way around. LCA is a robust and science-based tool to measure the impacts of the new circular economy products and business models." LCA analysis may reveal possible critical elements and challenges in terms of waste management system that includes recycling, LCA may show not only the potential impact but also assess avoided impacts that may be obtained via recycling. Product streams generated by waste treatment, such as valuable secondary raw materials or energy produced in the thermal waste treatment processes are called "benefit", and corresponds to the so-called avoided impacts on the environment as a result of replacing conventional processes with primary resources or other waste management strategies. However, during conducting such an analysis we can also note that some processes are dangerous or not really beneficial in the full life cycle, especially in different impact categories than abiotic depletion, for example, human health. In that case, it can be seen that we will save the raw materials but we will use many chemicals substances which are really dangerous for health, animals and fauna and flora. Future work should include all of the impact categories in order to keep the balance in a sustainable strategy of managing resources. It can also show, that we should rather replace the raw materials with new innovative ones than recycle it. Each case would indicate the complex problem of this.

Therefore, to get a better picture of the recycling system for end-of life PV modules, a full LCA analysis should be carried out and additional impact categories should be calculated for a functional unit, which is a crucial issue in LCA. The model boundaries of recycling system should include collection of PV waste, sorting, treatment processes of individual fractions adjusted to module type and the recovery. From the moment PV waste enters the recycling plant to until it leaves the system in the form of emission or as secondary raw material. The main goal of the analysis would be the assessment of the environmental performance of each process of different metal recovery strategy and verification if benefits arising from the material and energy recovery could offset the burdens due to the processing of the waste itself. The analysis could be conducted in SimaPro software, which defines the environment as: a set of biological, physical and chemical parameters constituting the conditions of human and nature well-being that are affected by humans. These conditions include human health, ecosystem quality and natural resources. Therefore, in order to determine the impact on environment it is necessary to analyse all three categories. Within the human health category, there are factors such as the number and duration of diseases, premature deaths due to environmental impact, and effects: ozone depletion, carcinogenic effects, radiation, obstructed respiration. Ecosystem quality includes the impact on species diversity and the following effects: climate change, ecotoxicity, acidification, eutrophication and land exploitation. The natural resource category includes surplus energy, which is the energy needed in the future to extract lower quality minerals, and the earth exploitation.

If we additionally include life cycle cost analysis, which is the economical approach to life cycle performance, it would be possible to identify the costs incurred during a life-cycle of a product or a service. Therefore, the result of such an analysis could be used in making investment decisions, that are very important in terms of recycling technology development.

The future study which could present close connection between circular economy and LCA analysis can help to achieve the goal of minimizing the raw materials depletion but in the balance of the other indicators, includes environmental, economic, and social impacts.

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