Material flow in photovoltaics from the perspective of circular economy

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Abstract

The photovoltaic (PV) sector is constantly 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. These raise 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, some proper management strategies should be adopted in order to close the loop. This work 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

1. Introduction

The constantly developing world consumes ever greater amounts of primary raw materials, and with their decreasing availability, as their resources are limited and not evenly distributed over the globe, raise the availability and security of supplies. It is known that the entire development of the economy is based on raw materials. Therefore, safe access to them is responsible for the proper functioning and growth of any economy.

As the economy grows, also energy demand could increase. The depleted reserves of fossil fuels are pushing humanity to seek alternative solutions. In a time of energy transformation and decarbonisation, our attention is focused on renewable technologies that have flourished in recent years, and they are still the subject of intense research and development.

Due to the implementation of more and more restrictive policies and regulations regarding global warming and environmental protection, both in Europe and around the world, the use of renewable sources is highly promoted since they contribute to the reduction of greenhouse gas emissions, diversification of energy supply and reduce dependence on uncertain and volatile fossil fuels markets.

The development of renewable energy favours a new model of the economy. The linear model, which is based on the principle of "produce, use, dispose” is slowly being replaced by a model based on circularity. The alternative, a new solution is a circular economy (CE) (EllenMacArthur, 2015).

It is a model which assumes that economic growth and welfare may be „decoupled” from environmental pressures and impact. Therefore, the economy can develop and grow without negative influence on the environment and additional resource usage, which causes many environmental problems (Ward et al., 2017). The key areas for the circular economy model are production, consumption, waste management, emission management, energy management and, above all, limiting the consumption of natural resources. It focuses on the creation, design and searches for new solutions and new business models that will reduce material consumption and generate savings throughout the whole supply value chain in any organisation or industry (Smol et al., 2019). One of the most important elements in the circular economy model is the implementation of eco-design principles when creating new products to reduce losses at the very beginning of the product development process (Gentilini and Salt, 2020). It is crucial to determine how products should be designed for modularity, future upgrades, repairs or deconstruction and recycling.

Therefore, according to the circular economy concept, products, materials and raw materials should remain within the economy as long as possible, and waste generation should be minimised as much as possible. Moreover, CE assumes that energy should come from a renewable source because the final goal of the circular economy is to promote the development of the economy independent from the use of non-renewable resources (Bachorz, 2017). Of course, nowadays, no European country can declare that all the energy it consumes comes from renewable sources. Nevertheless, they are taking actions to introduce renewable energy into their energy mixes and to reduce the use of fossil fuels for energy purposes.

Among renewable technologies, those using wind and solar energy play the most important role. They are also the cheapest form of clean energy production. The photovoltaic sector is one of the fastest growing renewable energy sectors in the world. It is expected that the share of energy from solar modules will increase. The growth of new PV installations is very dynamic. Such a development is a consequence of significant cost reductions and implementation of new regulations and supportive policies regarding this technology as well as research and development funds. If this trend continues, it is anticipated that the PV market will grow in the next three decades, according to IRENA (IRENA, 2019). Apart from the improvements related to 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 the estimates, in 2030, the power addition would reach 270 GW and 372 GW in 2050.

The high growth rate of new installations, observed since 2000, raises questions about end-of-life solar panels. It is obvious that photovoltaic technologies are ageing and have a specific lifetime of about 25-30 years, so one day, they become a waste (Paiano, 2015), (Rogala, 2020). However, such waste is full of very important and strategic components, like metals, which could be recovered in the recycling process. Thus, it is important to ensure that valuable raw materials do not end up in landfills. The provisions established by the WEEE Directive (DIRECTIVE 2012/19/EU) constitute the reference point for the development of this industry. Therefore, it will be necessary to develop infrastructure and facilities for the recycling of used modules in order to recover the valuable materials and in future fulfil the material demand.

This work aims to determine the capacity growth rates and material flows required to cover the demand for energy from photovoltaics up to 2100 based on different technology choices available on the market. Taking into account the available reserves, the year of depletion of individual metals was calculated, and bottlenecks in the production of PV modules were defined. Subsequently, the possibilities of recovering valuable metals in the recycling process and the impact of recycling on demand for primary metals were investigated as a practice promoted by a circular economy.

2. Methodology

According to the European Commission (EC), a 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 amount of materials flowing within the economy and precise how they are used and determine their level of circularity.

Such an approach may also be 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 the 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).

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. 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 the 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 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. In the next step, material savings from recycling were calculated considering different recycling ratios.

The purpose of such procedure was to illustrate the problem of depleting metals and also emphasise 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 extraction of primary materials. Using SimaPRO software abiotic depletion potential for each metal in the PV module was calculated, and then the values were converted for one module. Obtained results may be helpful in decision making or verifying which process could be modified to gain maximal environmental benefits concerning the availability of resources.

3. Results

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). It is presented in figure 1 below.

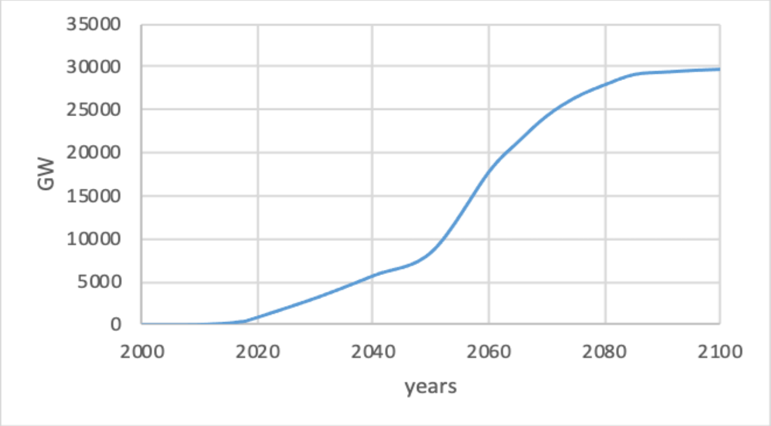

Figure 1. Power capacity in PV installation by 2100 (own work)

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 modules, CIGS and CdTe panels, which stand for the majority of technologies available on the market. In the next step, the material requirement over time was calculated, which was referred to the reserves of individual metals, resulted in the calculation of the depletion year, i.e. until when each metal will be available.

The obtained results made it possible to prepare a graph presented in figure 2, which shows the bottlenecks in PV production in terms of a secure supply of the strategic metals.

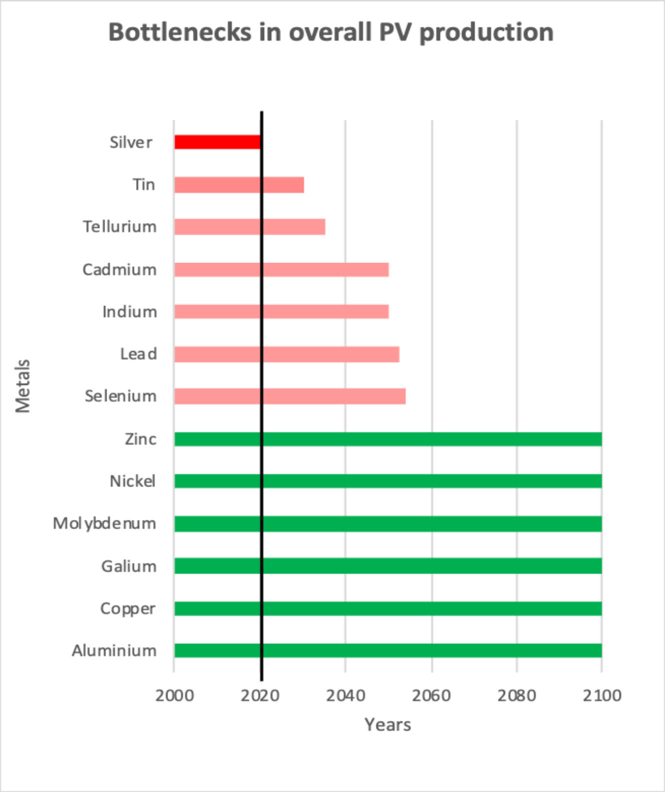

Figure 2. Material bottlenecks in the PV manufacturing process (own work)

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

In order to reduce the consumption of natural resources, the concept of a circular economy is implemented, which assumes that materials should remain within the economy as long as possible and the generation of waste is minimised. That is why waste recycling is used, which brings many ecological and economic benefits. Via recycling, it is possible to recover raw materials and save other goods such as energy and water and reduce greenhouse gas emissions. Table 1 presents material savings from the 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 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.

Results presented in Table 2 below shows the impact of the material recovery from recycling on the metals' depletion year.

Table 2. Depletion year taking into account recycling of end-of-life modules (own work)

Fraction	NO	15%	25%	50%	75%	85%	100%
Aluminium	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100
Cadmium	2050.05	2050.45	2050.74	2051.52	2052.42	2052.81	2053.45
Copper	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100
Glass	> 2099	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100
Galium	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100
Indium	2050.08	2050.48	2050.77	2051.55	2052.45	2052.85	2053.49
Lead	2052.65	2053.15	2053.51	2054.48	2055.59	2056.09	2056.88
Molybdenum	> 2100	>2100	> 2100	> 2100	>2100	>2100	> 2100
Nickel	> 2100	> 2100	> 2100	> 2100	>2100	> 2100	> 2100
Selenium	2054.30	2054.84	2055.29	2056.45	2057.70	2058.22	2059.04
Silicon	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100
Silver	2020.27	2020.27	2020.27	2020.27	2020.27	2020.27	2020.27
Tellurium	2065.92	2069.47	2069.65	2070.17	2070.87	2071.21	2071.84
Tin	2030.07	2044.26	2044.66	2045.86	2047.49	2048.32	2049.83
Zinc	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100	> 2100

It is visible that the recycling of PV modules reduces the need for primary materials. However, taking into account the individual metal it does not significantly affect the moment of depletion. Therefore, secondary materials would not be able to cover a whole new material demand. Nevertheless, end-of-life modules should be recycled to recover many valuable minerals and to make the PV technology sustainable.

In the last point, the abiotic depletion index was calculated for each of the metals used in the production of the photovoltaic module, using the SimaPRO software. The CML methodology was implemented, which is often considered as a complete methodology because it deals with different environmental impacts (Hischier et al., 2010).

Depletion of abiotic resources is one of the baseline impact categories. It is related to the protection of human and ecosystem health and welfare. 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, 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 (Van Oers and Guinée, 2016).

Figures 3-5 contain information about abiotic depletion of metals recalculated for each photovoltaic technology: c-Si, CdTe and CIGS/CIS modules.

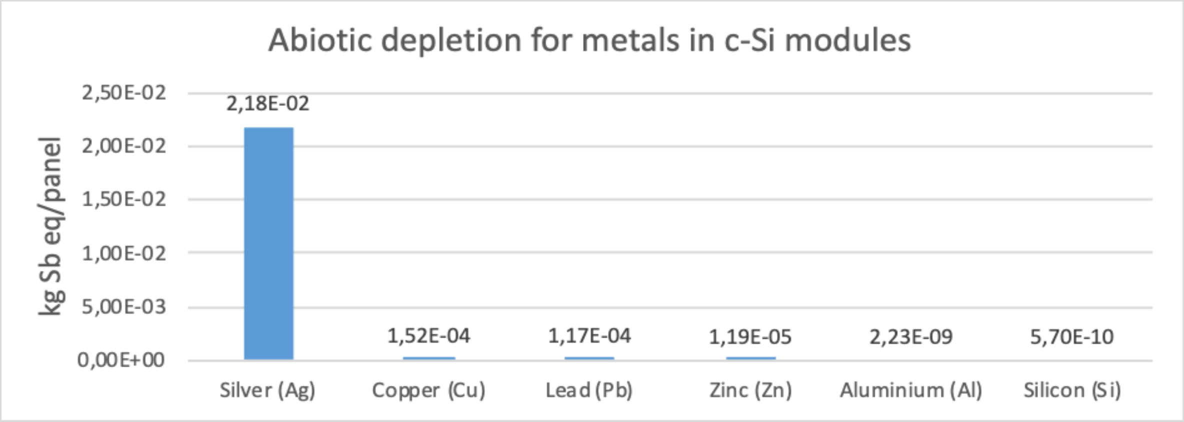

Figure 3. ADI for metals used in c-Si module production (own work based on Ecoinvent database)

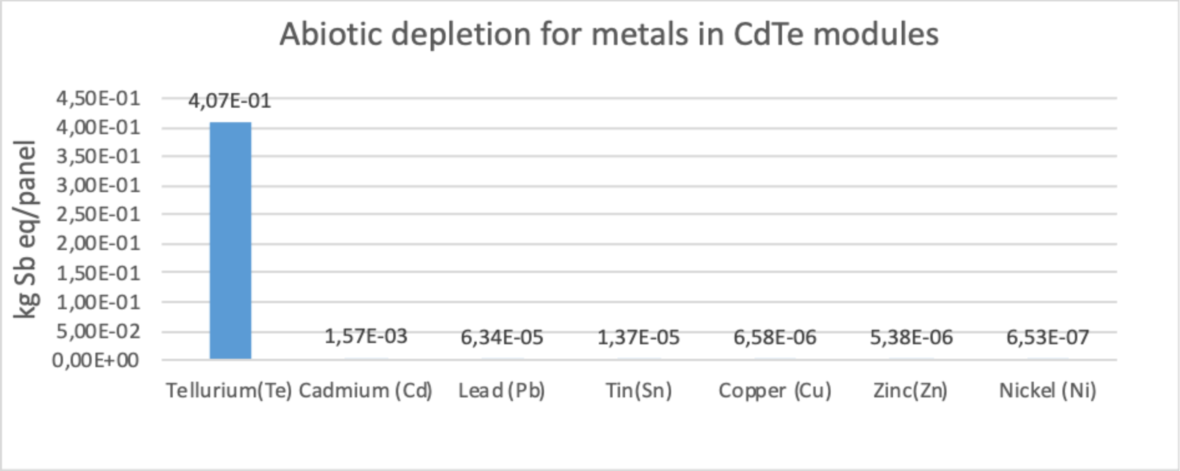

Figure 4. ADI for metals used in CdTe module production (own work based on Ecoinvent database)

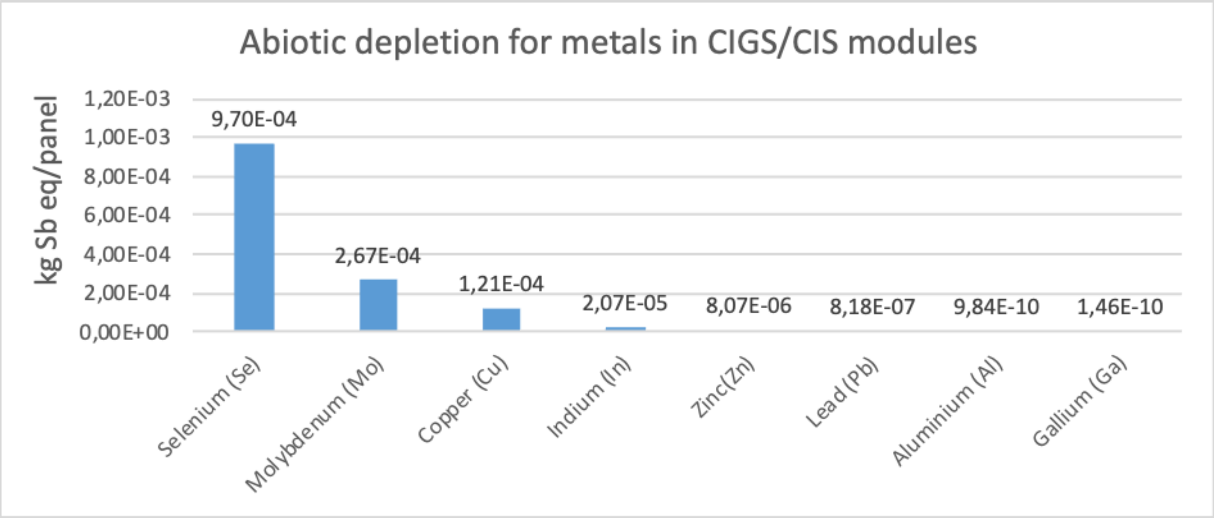

Figure 5. ADI for metals used in CIGS/CIS module production (own work based on Ecoinvent database)

It can be seen that the most depleting metals are silver, tellurium and selenium. Therefore, their level should be observed carefully. What is more, we should be aware 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 can be measured. 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. That is why the abiotic depletion impact parameter is heavily debated (van Oers et al., 2019). However, future resource availability for metals should consider recycling as well as any losses in the whole value chain.

4. Conclusions

Based on the results achieved in this work, it can be concluded that the switch to a low-carbon electricity mix would result in great demand for metals. It will depend on assumptions about technological choices as well as the development of material intensity and energy scenarios. What is more, photovoltaics makes a large contribution to this phenomenon. The framework developed in this thesis may be useful for the assessment of material consumption in particular technologies and will be necessary for developing strategies to solve problems with the availability of materials and to reduce harmful impact on the environment and economy, due to extraction and processing of primary resources.

As a result of the analysis, estimated dates of depletion of metal reserves intended for the production of photovoltaic modules were obtained, and bottlenecks that may block the manufacturing process of new technologies were explored. Metals that can run out the fastest are silver, tin, tellurium, cadmium, indium, lead and selenium. Therefore, the greatest attention should be focused on these materials when designing products. Furthermore, research and development in terms of recovery and substitution possibilities of these metals should be considered in priority.

It is hard to say whether the availability of materials may limit the future deployment of photovoltaics. However, ensuring this amount of raw materials will be a big challenge, considering the technologies available on the market. Several simplifications were adopted in this analysis. Among other things, it was assumed that only two generations (first and second generation) were available on the market, and their shares were constant during the whole analysed period. However, the reality is more complicated, and the situation is changing dynamically. Therefore, the analysis should be extended in the future and material flows going within PV industry should be updated, taking into account new possible technological solutions and technological development in terms of material efficiency, durability, power generation capacity, and new eco-design strategies.

As for the assumptions of the circular economy in the PV industry, attention was focused on the final stage of the PV module lifecycle, i.e. management of end-of-life panels. It can be seen that the recycling of end-of-life modules does not play a big role until 2100. Even with 100% recycling rate will not significantly delay the metal depletion and 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, independent of primary materials supplies and enable maintaining a low-carbon energy system in the long term, because it may provide with a large number of materials.

It should also be remembered that apart from photovoltaics, there are other technologies that are fostering green and digital transition, such as wind farms, batteries or clean mobility. Similar to photovoltaics they are characterised by a high metal intensity, including those consumed by PV industry. Therefore, interactions with other industries that require the same materials as PV must be considered in order to comprehensively assess constraints caused by the availability of materials for growing PV. The photovoltaic industry for most of the analysed metals currently represents only a fraction of current production. It can, therefore, be concluded that the increased demand will result in increased competition between different industries. Since, batteries, which are an essential component of any renewable energy system, deserve special attention in terms of metal requirements, especially lithium. 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.

To sum up, the era of “take, make, dispose of” is coming to an end. This model of the economy is becoming inefficient, and the scarcity of resources makes it impossible to maintain. In order to accelerate the transformation of the energy system to the new circular model, the products, including PV modules, should be designed with the reduction, reuse and upcycling in mind. This is one of the key research areas 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. Hence, shifting to a “closed-loop” 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. Moreover, by combining circular economy with the life cycle analysis (LCA), it will be possible to introduce new strategies that will ensure sustainable innovation.

References

Bachorz, M. (2017). Polska droga do gospodarki o obiegu zamkniętym – opis sytuacji i rekomendacje. ISBN 978-83-947616-0-8

Bringezu S (2006). Materialising policies for sustainable use and economy-wide management of resources: Biophysical perspectives, socio-economic options and a dual approach for the European Union. Wuppertal Institute for Climate, Environment and Energy. Available online: https://epub.wupperinst.org/frontdoor/deliver/index/docId/2390/file/WP160.pdf. Accessed 12 Mar 2020.

Brunner, P.H., Rechberger, H. (2004). Practical handbook of material flow analysis. The International Journal of Life Cycle Assessment 9(5):337-338.

Commission of European Communities (2015). Communication No. 614, 2015. Closing the loop-an EU action plan for the circular economy (COM no. 614, 2015).

DIRECTIVE 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union.

Ellen MacArthur Foundation (2015). Towards a Circular Economy: Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation Publishing.

Gentilini, E., Salt, M. (2020). Circular photovoltaics: circular business models for Australia's solar photovoltaics industry, Arup.

Hischier, R., Weidema, B., Althaus, H.J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Koellner, T., Loerincik, Y., Margni, M., Nemecek, T. (2010). Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.2.

IRENA (2019). Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), International Renewable Energy Agency, Abu Dhabi.

IRENA (2020). Global Renewables Outlook: Energy transformation 2050 (Edition: 2020), International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-238-3.

Paiano, A. (2015). Photovoltaic waste assessment in Italy. Renewable and Sustainable Energy Reviews, 41, 99–112. doi:10.1016/j.rser.2014.07.208.

Rogala, B. (2020). Recykling paneli słonecznych może przynieść zyski wysokości 15 mld dolarów Available online: https://300gospodarka.pl/news/recykling-paneli-slonecznych-moze-przyniesc-zyski-wysokosci-15-mld-dolarow Accessed 19 August 2020.

Smol, M., Kulczycka, J., Czaplicka-Kotas, A., Włóka, D. (2019). Zarządzanie i monitorowanie gospodarki odpadami komunalnymi w Polsce w kontekście realizacji gospodarki o obiegu zamkniętym (GOZ). Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN. 108. 165-184. doi:10.24425/znigsme.2019.130174.

Van Oers, L., Guinée, J.B., Heijungs, R. (2019). Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. The International Journal of Life Cycle Assessment. doi: 10.1007/s11367-019-01683-x.

Van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J. et al. (2011). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Climatic Change 109, 95. doi:10.1007/s10584-011-0152-3.

Ward, J. Chiveralls, K., Fioramonti, L., Sutton, P., Costanza, R. (2017). The decoupling delusion: rethinking growth and sustainability. Available online: https://theconversation.com/the-decoupling-delusion-rethinking-growth-and-sustainability-71996. Accessed 19 April 2020.