Recyclability and ecological-economic analysis of a simple photovoltaic panel

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Abstract *– Photovoltaic industry has displayed an exponential expansion rate over the past two decades. Currently, 1185 GW of the global electricity demand is derived from photovoltaic (PV) panels with more to come in the next two decades. With the growing installment rate, a concern regarding managing panels that reached the end of their life-span grows. Despite the fact that the approximate life-span of a panel is 25 years, oftentimes this interval is shortened due to weather conditions, low-quality installations, and poor maintenance. Therefore, a global attention is focused on research and law-regulation of proper recycling and disposal of the PV waste. In this contribution, recyclability of one PV panel is determined upon subjecting it to the simplest recycling process, which is manual mechanical separation using common hand-tools. In addition, an ecological-economic analysis of the panel, which yields an absolute profit of the panel is presented.*

***Keywords**:* *photovoltaic panel, recyclability analysis, ecological-economic analysis, waste management*

1. INTRODUCTION

Since the industrial revolution, the enormous rate of the world's energy demand has resulted in a high consumption of fossil fuels, which has had a detrimental impact on the environment due to a concerning release of greenhouse gases into the atmosphere. Negative environmental impact of such consumption was/is on the urgent agenda of major global organizations as recently confirmed by the United Nation Secretary-General's opening remarks at the press conference on climate where it was stated that "the era of global warming has ended; the era of global boiling has arrived" [1]. Hence, renewable energy resources gained attention and are being developed by generating electric power with nearly zero pollution [2].

However, at the moment, renewable energy supplies short to quarter of electricity in the world. After reflections and absorptions, around 100 000 terawatts of the total irradiated energy from the Sun reaches the Earth's surface, which is a tremendous quantity of "free" energy. Despite this potential, solar energy is only the third contributor in the global clean energy network, after wind and hydro energy [3]. Of the total energy produced globally, 29.9% is produced from renewable sources. Hydropower is the biggest contributor with 15.1% followed by wind and solar energy which amount to 15.1% combined [4]. In spite of the wind and solar energy lower figures, the rate of wind turbines and solar panels instalments is quick, and the outlook seems positive.

Recently, an un-heard rate of expansion was displayed by the photovoltaic industry. Over the last 16 years, power derived from PV panels installed globally increased by over 60 times at the exponential rate, i.e. from 9.1 GW in 2007 to over 300 GW in 2016 [5], whereas the current state of the art is determined at around 1185 GW [4] of the global electricity demand. This remarkable achievement is possible due to severally combined reasons: decreased production costs of PV panels, increased PV panel efficiency, and improved PV panel dependability. The advancement of PV solar cells is probably the key of the PV industry success. PV cells are essentially a semiconductor that has been engineered to effectively absorb irradiated solar energy and transform it into the electrical energy. PV cells are connected and protected from the environment in PV modules, which are the fundamental components of PV systems. Therefore, the photovoltaic installation capacity would have reached 4500 GW by 2050 is of no surprise [6].

Consequently, it is predicted that solar waste will have accounted for up to 14% of the total generation capacity by 2023, with the assumption that the PV panel lifespan is 25 years. A further projection is 78 million tons of waste by 2050, which is 80% of the overall production capacity [7]. As a result, the use of photovoltaic modules is a substantial environmental, social, and economic challenge in the years to come, particularly in light of the advocated notion of sustainable production and the European Green Deal [8]. The European Green Deal, a document outlining a precise set of targeted steps to combat climate change, was released by the European Commission in 2019. By 2050, Europe must stop producing net greenhouse gas emissions in order to achieve the target. To separate economic progress from resource waste, the development paradigm itself must be modified. It is an ambitious initiative that will have an impact on tens of millions of people which the major institutions of Europe will work tirelessly for years. Europe will be the first continent to attain climate neutrality if the accord is successfully implemented. Some advancements have been made due to the European Union issuing the Guideline 2012/19/EU (replacing the earlier 2002/96/EU) [9]. According to this Guideline, end-of-life photovoltaic panels must be regarded as electrical and electronic equipment waste (WEEE). On the other hand, based on observations of global market realities, there is currently no clear plan for handling waste from the PV industry sector. For example, India is the fifth solar PV power producer in the world, but has no laws which dictate safe disposal of solar energy waste [10].

Aggravating circumstance is a lack of knowledge of the precise quantity and kind of this type of waste that has previously been transferred and put in national landfills. Furthermore, there is no specific statute dealing with the guidelines for processing solar power waste under the applicable laws and there is no regulation over the usage or import of this kind of waste. Also, the conflict between Russia and Ukraine seems to raise a lot of questions about the Green Deal. Due to the scarcity of natural gas from Russia, there are some intentions to start using coal to generate energy, but there is no significant plan with a renewable solution in place for the upcoming years [11].

Therefore, the motivation for this research is a growing concern about managing photovoltaic panels that reached the end of their life-span. For this purpose, two analyses were conducted and are presented in this paper. Firstly, we analyzed the recyclability of a simple photovoltaic panel that was manually mechanically separated in a manner and with tools that the average user would be able to perform. Secondly, we analyzed the cost and income from recycling the panel to determine if recycling is the optimal option at the current state of the art.

2. PV PANEL LIFE-SPAN AND RECYCLING

Solar power solutions can be roughly divided into two types: solar thermal and photovoltaic.

Solar thermal applications include residential hot water heaters, cooking, solar water purification, molten salt energy storage, solar power transmission, fuel production, and Concentrated Solar Power (CSP). The CSP employs mirrors, which are often parabolic troughs or dishes, to direct and track Sun rays on the working fluid. Expanding and vaporizing heated fluid powers a turbine. The conversion of solar energy into heat, which can be easily stored, is a major benefit of CSP. In the case of photovoltaic systems, converted electric energy is more challenging to store despite advancements in the battery technology.

Solar PV panels convert energy directly. Panels are most effective in direct solar radiation, but also operative in diffuse cloudy solar radiation, which makes them a compelling green solution. When Sun rays strike a solar panel, which is still the most frequently made of 99.9999% purity silicon, it releases electrons, i.e., electric current. Not long ago, the only solar panels on the market were constructed of pure silicon, which is expensive and requires a lot of energy to produce. A variety of innovative solar panels has been created as a result of wafer technology research, including those made of cadmium telluride, indium-copper-gallium alloys, and perovskites.

As briefly mentioned in the introductory part, the approximate life-span of a photovoltaic panel is 25 years. More often than not, a panel life-span is shortened due to occurrences as [12]:

- extreme weather conditions;
- catastrophes caused by nature;
- building blazes;
- high rate of low-quality rooftop panel installations;
- financial incentives to remove panels before they reach the end of their life-span;
- discouragement to replace one rooftop panel rather than the entire system;
- improper installation sites;
- poor or no maintenance;
- moisture penetration;
- damage during transit or installation.

In comparison to other electric energy sources, solar PV panels are thought to produce an excessively large quantity of waste per unit of energy [13]. However, due to the rising demand for renewable energy to reduce carbon dioxide emissions, PV panels are to be used more frequently, which is in contrast with the waste management hierarchy that lists prevention of waste as a preferable method above reducing, reusing, recycling, and lastly disposing of the waste. Coincidently, the same reasoning eliminates reducing as a method of PV waste management. The reusing method should get more attention in the future as there is a potential market for second-hand PV panels. After a life-span of operation, a panel's efficiency is lowered to over 80% compared to its initial efficiency due to the natural decay of the photovoltaic cells caused by solar irradiation [14]. This is because the efficiency of the panels declines at a rate of roughly 1% per year. Note that [14] refers to the natural decay and excludes the waste produced by the circumstances previously listed in this section. That said, even if reused, PV panels will eventually become a waste, which leaves recycling as an optimal option. To put in a perspective, half of carbon footprint of producing a photovoltaic panel is due to converting raw materials into cells, cables, and frame, but if a panel is recycled, almost 80% of raw material can be recovered [10].

Currently, PV panels are subjected to one out of three recycling processes: mechanical separation, thermal treatment, and chemical treatment [15].

Mechanical separation is disassembling of PV panels by removing encircling aluminum frames, junction boxes, and imbedded cables. Panels, junction boxes, and cables are the components of PV modules that are shredded and crushed to check each component's individual toxicity and the module's overall toxicity before disposal. The aluminum frame component can be recovered through secondary metallurgy after being detached from the module. Iron, silicon, and nickel are considered small quantity elements that are typical components of aluminum alloys and are further reused.

By thermal and/or chemical treatment, a solar panel is delaminated, its chemical components are separated, and the pure silicon inside is extracted. The outcomes of research in this field are encouraging, but there is still a lack of efficiency on a broad scale. Additionally, this recycling method still faces difficulties with regard to its commercial feasibility due to the creation and required treatment of dangerous gases.

3. RECYCLABILITY ANALYSIS

In this paper, a simple PV panel was disassembled to elements via mechanical separation using basic tools to prepare the PV panel for a recyclability evaluation method. This method analyzes a product as an assembly composed of a certain number of elements [16], and assigns to them dimensionless coefficient R which indicates product's (re)processability potential.

The coefficient R, simply called recyclability, can assume values that separate the product in three categories:

- desirable recyclability $1.00 \geq R \geq 0.75$;
- need for product reconstruction or selective disassembly $0.74 \geq R \geq 0.50$;
- down-cycling procedures (lower quality recyclates) or disposal $R \leq 0.49$.

The photovoltaic panel from the study is model MODULE SL30 AA, manufactured by SOLE. Figure 1 (top) shows the studied panel before mechanical treatments, and Fig. 1 (bottom) shows the panel disassembled using pliers, screwdriver, scalpel, spatula, and blow-dryer. The steps done in manual mechanical separation of the panel into elements are listed in Table 1, as well as the time duration of each step. The next process in recycling would be a chemical separation of metal from the anti-reflective (AR), P, and N layers, but it was omitted in this paper.

Fig. 1. PV panel MODULE SL30 AA under study, before (top) and after (bottom) a manual mechanical separation

The recyclability analysis of the product includes determination of elementary indicators and the calculation of complex indicators. The quantitative results are expressed as ratios of the sum of the recyclability of individual parts and the ideal (maximum) recyclability.

Table 1. Manual mechanical separation of the PV panel from the study.

Procedure	Duration (s)	Cumulative duration (s)	Tool
Separating aluminum frame	87.13	87.13	Pliers
Separating fuse box	31.14	118.27	Screwdriver
Removing screws from the fuse box	44.58	162.85	Screwdriver
Removing wires	204.04	366.89	Pliers
Removing protective foil	359.66	726.55	Scalper
Removing layers (AR, P, N)	2880.31	3606.86	Spatula Blow-dryer

Evaluation of recyclability depends on the product structure, type of material, and types of connections [17]. Finally, the recyclability R is determined as:

$$R = \sum_{i=1}^{n} m_i b_i r_i \frac{1}{M\, r_{max}}, \quad (1)$$

where m_i is the mass of the i-th element in grams, b_i is the number of repetitions of the i-th element in the product, r_i is the recyclability rating of the i-th element, M is the total mass of the product in grams, and r_{max} the highest recyclability rating. Upon determination of the type of the material elements of the PV panel are made of, mass of each element was measured with the analytic scale Kern ALS 220-4N, sensitivity 0,01 g. The results of the recyclability analysis are shown in Table 2. Note that M in Eq. 1 is a sum of mi (Table 2). Based on the data presented in Table 2, and according to Eq. 1, photovoltaic panel recyclability was obtained to be $R = 0.73$. This suggests that the panel should be reconstructed rather than recycled.

Table 2. Recyclability analysis of the PV panel.

Element	Material	Mass (g)	Repetition	Rating of recyclability	Recyclability of the element
i	v_i	m_i	b_i	r_i	$m_i b_i r_i$
Frame	Aluminum	141	1	5	705
Screw	Steel	0.5	4	5	10
Fuse box	Polymer	35	1	2	70
Wire	Copper	22	1	5	110
Foil	Unknown	184	1	2	368
AR+P+N	Hazardous waste	157	1	0	0
Glass cover	Glass	2200	1	4	8800

4. ECOLOGICAL-ECONOMIC ANALYSIS

The ecological-economic analysis model is based on the calculation of cost and income from recycling, and for the assumed method of disposal, it provides the user with data on the absolute profit.

Total recycling cost T is a sum of disassembly T_{da}, shredding T_s, recycling T_r, and disposal costs T_d [18]:

$$T = T_{da} + T_s + T_r + T_d. \quad (2)$$

Total income from recycling P is a sum of income from the sale of recycled materials P_s, income from energy savings P_{es}, and income from emission reduction P_{er} [18]:

$$P = P_s + P_{es} + P_{er}. \quad (3)$$

Finally, the profit from recycling DA is simply the difference between the total income and total costs:

$$DA = T - P. \quad (4)$$

The cost of disassembling of the analyzed PV panel depends on the duration of this process, which is 1.002 hours, as determined from Table 1, and the cost of required labor per hour, whose average is € 10. Hence, disassembling cost is obtained as € 10.02. Upon disassembly, the remaining parts were fairly small (Fig. 1), and further shredding was not required, so $T_s = 0$. Recycling and disposal costs are shown in Table 3, and are predetermined by the cost of recycling/disposing of individual material per unit of mass.

Table 3. Costs of recycling and disposing of the analyzed PV panel

Recycling			
Element	Cost per kg	Mass (kg)	Tr
Aluminum	0.65	0.141	0.0917
Copper	0.65	0.225	0.1463
Polymer	0.65	0.219	0.1424
Glass	0.65	2.200	1.4300
	Total	2.785	1.8103
Disposing			
Element	**Cost per kg**	**Mass (kg)**	**Td**
Hazardous waste	0.40	0.157	0.0628

Therefore, according to Eq. 2, the total recycling cost of the PV panel is $T = 11.89$ €, as shown in Fig. 2.

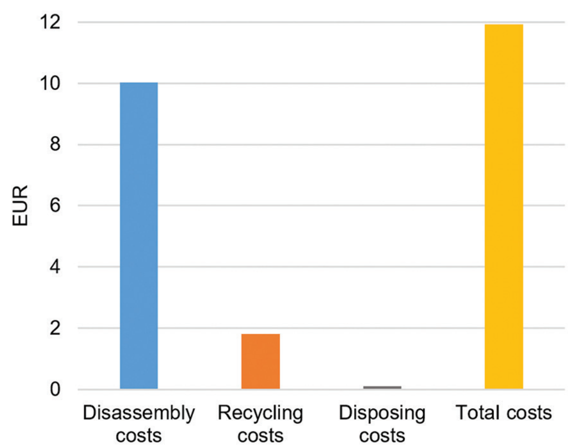

Fig. 2. Costs of recycling.

Table 4. Income analysis.

Recyclate	Mass	Price	Income from sale	Energy savings	Income from energy savings	Emission reduction	Emission fee	Income from emission reduction	Total income
r	M_r (kg)	P_r (€)	$P_s=M_rP_r$	*/\e (€/kg)*	*Pes=Mr/\e*	E	p_e	$P_{er}=M_rEp_e$	P
Aluminum	0.141	4.20	0.59	1.200	0.17	4.5	0.80	0.51	1.27
Copper	0.225	6.20	1.40	0.300	0.07	1.2	0.80	0.22	1.69
Polymer	0.219	0.18	0.04	0.020	0.05	0.9	0.80	0.16	0.25
Glass	2.200	2.00	4.40	0.600	1.32	1.2	0.80	2.11	7.83

Plugging the data into Eq. 3 gives the total income from recycling one PV panel P = 11.45 €. The income from recycling, according to the type of the material, is shown in Fig. 3.

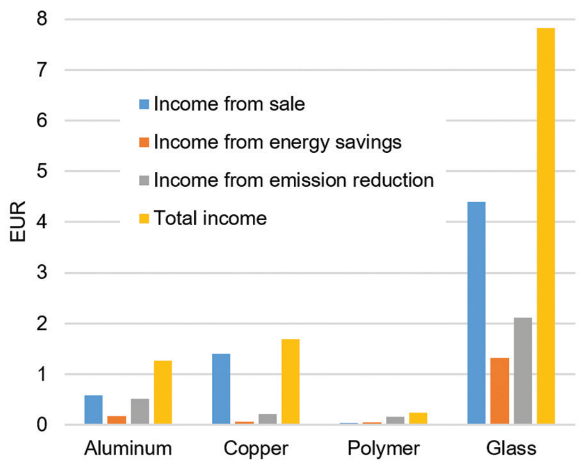

Fig. 3. Income from recycling

The obtained data on the total costs were compared with the total income from recycling, and the profit was calculated according to Eq. 4. Data analysis indicates that the profit from recycling one photovoltaic panel is negative. A user would make a loss of € 0.44 to manually recycle one PV panel on his own. This outcome is due to the high cost of disassembly caused by the long process of disassembling the PV panel. In addition, the amount of hazardous waste to dispose is large, relatively to the total mass of individual elements of the PV panel that can be recycled.

5. CONCLUSIONS

In this paper, recyclability and ecological-economic analyses of one simple photovoltaic panel are presented. To prepare the PV panel for the analyses, a manual mechanical separation of the panel into the building elements was performed using common hand tools and blow-dryer. Disassembling process resulted with 7 different components which took 6 operations that lasted for over 1 hour in total. The most challenging operation was removing the anti-reflective, P, and N layers from the panel, for which a spatula and blow-dryer was used.

The recyclability analysis showed that the PV panel recyclability is 73%, which indicated that this product should be either reconstructed or further selectively disassembled, rather than recycled after a mechanical separation only.

By applying the model of the ecological-economic analysis, it was determined that there is a negative profit from recycling the PV panel. The analysis showed that there is € 0.44 loss for recycling and disposing of one panel. The loss is the consequence of a long procedure of disassembling the panel into components, high share of hazardous waste, which requires disposing, in comparison to materials that can be recycled, and a certain share of unknown polymers that were not labeled on the product.

Therefore, to increase the recyclability of PV panels, manufacturers should adhere to the design guidelines for increasing the recyclability of electronic devices and equipment. One way to achieve this is by using well-known polymers that have a label of their type, which facilitates the sorting of parts and achieves a higher price for recycling material. Additionally, the use of simpler components would make the construction more modular and would result in easier and faster disassembly of PV panels.

Note that the estimates of prices were used in this paper, therefore, a certain error may have been introduced into the outcome of the ecological-economic analysis. Considering that the method of manual disassembly of PV panels did not give a positive profit, the chosen method of disassembly is not ideal. It is recommended to use a combination of a manual and strictly mechanical disassembly to increase the process speed.

6. REFERENCES

[1] United Nations, "Secretary-General's Opening Remarks at Press Conference on Climate", https://www.un.org/sg/en/content/sg/speeches/2023-07-27/secretary-generals-opening-remarks-press-conference-climate (accessed: 2023)

[2] P. Nema, R. K. Nema, S. Rangnekar, "A Current and Future State of Art Development of Hybrid Energy

System Using Wind and PV-Solar: A Review", Renewable and Sustainable Energy Reviews, Vol. 13, No. 8, 2009, pp. 2096-2103.

[3] T. Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, N. Prabaharan, "A Comprehensive Study of Renewable Energy Sources: Classifications, Challenges and Suggestions", Energy Strategy Reviews, Vol. 43, 2022, p. 100939.

[4] REN21, "Renewables 2023: Global Status Report", UN Environment Programme, https://www.ren21.net/gsr-2023 (accessed: 2023)

[5] T. Letcher, V. M. Fthenakis, "A Comprehensive Guide to Solar Energy Systems: With Special Focus on Photovoltaic Systems", Academic Press, 2018.

[6] M. Niekurzak, W. Lewicki, H. H. Coban, A. Brelik, "Conceptual Design of a Semi-Automatic process line for Recycling Photovoltaic Panels as a Way to Ecological Sustainable Production", Sustainability, Vol. 15, No. 3, 2023, p. 2822.

[7] Statista, "Projected Cumulative Volume of Solar Photovoltaic Panel Waste Worldwide from 2016 to 2050", https://www.statista.com/statistics/565743/solar-pv-panels-waste-projection-worldwide/ (accessed: 2023)

[8] EUR-Lex-52019DC0640-EN, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed: 2023)

[9] "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC And 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC", https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02012L0027-20200101&from=NL#:~:text=This%20Directive%20establishes%20a%20common,way%20for%20further%20energy%20efficiency (accessed: 2023)

[10] J. Malaviya, "Need for Legal Compliance for Safe Solar Energy Waste Disposal", Proceedings of the European Photovoltaic Solar Energy Conference and Exhibition 2020, Online: Virtual Conference and Exhibition, 7-11 September 2020, pp. 1204-1208.

[11] F. Simon, "With Russian Gas Gone, Coal Makes EU Comeback as 'Traditional Fuel'", https://www.euractiv.com/section/coal/news/with-russian-gas-gone-coal-makes-eu-comeback-as-traditional-fuel/ (accessed: 2023)

[12] P. Majewski, W. Al-Shammari, M. Dudley, J. Jit, S. H. Lee, K. Myoung-Kug, K. Sung-Jim, "Recycling of Solar PV Panels-Product Stewardship and Regulatory Approaches", Energy Policy, Vol. 149, 2021, p. 112062.

[13] S. F. Baldwin, "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities", USA Department of Energy, 2015.

[14] V. Sharma, S. Chandel, "Performance and Degradation Analysis for Long Term Reliability of Solar Photovoltaic Systems: A Review", Renewable and Sustainable Energy Reviews, Vol. 27, 2013, pp. 753-767.

[15] M. S. Chowdhury, K. S. Rahman, T. Chowdhury, N. Nuthammachot, K. Techato, M. Akhtaruzzaman, S. K. Tiong, K. Sopian, N. Amin, "An Overview of Solar Photovoltaic Panels' End-of-Life Material Recycling", Energy Strategy Reviews, Vol. 27, 2020, p. 100431.

[16] M. Kljajin, M. Opalić, A. Pintarić, "Recikliranje električnih i elektroničkih proizvoda", Mechanical Engineering Faculty in Slavonski Brod, Slavonski Brod, Croatia, 2006. (in Croatian)

[17] H. Martens, D. Goldman, "Recyclingtechnik: Fachbuch fur Lehre und Praxis", Springer, 2016.

[18] A. Pintarić, "Assessment of Recyclability for Electrical Waste", Proceedings of the 13th International Symposium on Waste Management, Zagreb, Croatia, 6-7 November 2015, pp. 347-355.