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# SOCIAL DIMENSIONS OF RECYCLING OF PHOTOVOLTAICS PANELS – CONCEPTUAL FRAMEWORK BASED ON LITERATURE REVIEW

 

**Abstract**

The widespread use of photovoltaic panels allows the use of renewable solar energy in place of conventional energy sources, but at the same time such approach most often does not take into account the total environmental costs, like all the costs related to their withdrawal from the market after their period of greatest efficiency or after their damage, i.e. costs related to the end of life (EOL) comprehended in numerous ways, and thus recycling. In India, it has been estimated that over 2.95 billion tons of photovoltaic waste may be generated in the years 2020-2047, in the USA 9.8 billion tons, in Mexico 1.2 billion tons, and in Australia from the recovery of materials from photovoltaic panels can reach even USD 1.2 billion. Due to the fact that the concept of recycling photovoltaic panels is relatively new from the point of view of researchers' interests, there is a need to create a conceptual framework at the level of social dimensions of recycling photovoltaic panels, due to the fact that this aspect has so far been analyzed primarily in terms of economic and ecological aspect. To fill this gap, the method of systematic literature review was chosen, the aim of which was to create a conceptual framework and identify key social factors influencing the behavior related to the recycling of photovoltaic panels, both by households and industrial installations and solar farms.

**Keywords:** *recycling; photovoltaic panels; management; social economy; sociology*

## 1. Introduction

It is widely believed that the widespread use of photovoltaic panels does not pose any threat to the environment and may rather generate environmental, economic and social benefits [1-3], allowing the use of renewable solar energy in place of conventional energy sources, which in turn may ultimately lead to reduction of greenhouse gases [4]. Nevertheless, such an approach most often does not take into account the total environmental costs, i.e. not only the benefits of using photovoltaic panels on a micro or macro scale (micro power plants for households and industrial power plants, solar farms), on the level of obtaining an energy source as opposed to non-renewable sources, but above all the costs related to their withdrawal from the market after their period of greatest efficiency or after their damage, i.e. costs related to the end of life (EOL) comprehended in numerous ways, and thus recycling.

For example, China, which has a huge number of solar power plants, currently operates about twice as many solar panels as the US and does not have a comprehensive approach to recycling them (i.e. taking into account legislative, economic, ecological and social aspects). On the other hand, despite potentially greater environ-mental awareness, California, another world leader in the use of solar panels, also does not have a standardized and comprehensive plan for the disposal of solar panels. Only Europe and the United Kingdom require solar panel manufacturers to collect and store waste resulting from their use [5]. Another key aspect is the economic resources of the country, which would support the industry related to the recycling of photovoltaic panels, and just as economically more developed countries are able to create and introduce standards related to the recycling of photovoltaic panels, so are the developing ones, which over the last decade particularly heavily invested in renewable energy (e.g. Po-land with over 1 million photovoltaic micro-installations, installed in less than the last decade)), may face this significant problem in the future. Allowing for the fact that photovoltaic panels have a long lifespan, their post-efficiency environmental impact has not been widely discussed among researchers. However, thanks to analyses indicating the enormity of the problem that some countries are already beginning to face, and others will be in the near future, an increasing number of researchers are beginning to attempt to analyze aspects related to the recycling of photovoltaic panels not only from the perspective of environmental costs, but also from the perspective of ecological, economic and social aspects of their recycling. Based on this outline, there are more and more studies showing the scale of the problem. In India, it has been estimated that over 2.95 billion tons of photovoltaic waste may be generated in the years 2020-2047 [6], in the USA 9.8 billion tons [7], in Mexico 1.2 billion tons [8], and in Australia from the recovery of materials from photovoltaic panels can reach even USD 1.2 billion [9], and due to the fact that the increase in energy prices resulting from various types of economic crises, and even military events, only accelerate the willingness to decide not only for individual consumers to invest in increasing their energy independence [10-11], but it is also one of the elements of the broadly understood energy transformation of various sectors of the economy [12], which is also part of the comprehensive digital transformation of these

enterprises. Many countries have a significant share of PV in terms of renewable energy generation, however most list PV waste as e-waste, which of course is an important step towards regulated end-of-life management and may offer opportunities for PV recycling legisla-tion if a country has legislation at all regarding the recycling of electronic waste. It is obvious that the penetration of renewable energy in all created energy is the way to a better and more sustainable future of cities, regions and countries [13-14], however, the recycling of photovoltaic panels may in the future pose a serious threat to solid waste management, however, as it is fully justified economically and ecologically, the condition for its effectiveness is taking steps towards a comprehensive social transformation at the level of understanding the importance of the need to recycle photovoltaic panels in a manner standardized by society.

## 2. Materials and methods

Due to the fact that the concept of recycling photovoltaic panels is relatively new from the point of view of researchers' interests, there is a need to create a conceptual framework at the level of social dimensions of recycling photovoltaic panels, due to the fact that this aspect has so far been analyzed primarily in terms of economic and ecological aspect. To fill this gap, the method of systematic literature review was chosen, the aim of which was to create a conceptual framework and identify key social factors influencing the behavior related to the recycling of photovoltaic panels, both by households and industrial installations and solar farms. This systematic literature review is primarily intended for policymakers, PV industry stakeholders, waste management professionals, and researchers seeking to develop effective strategies for PV panel recycling. By identifying key social factors that influence recycling behaviors, this review provides an evidence-based foundation for designing targeted interventions that can increase public participation in PV recycling programs before the waste crisis materializes. There are many methods of review aimed at creating a conceptual framework for a given area or systematizing knowledge and identifying research gaps in a given issue [15], such as critical review, structured literature review, meta-analysis, systematic

search and literature review in general [16]. As part of the research, a systematic review of the literature was carried out in order to structure knowledge [17-18] in the field of social aspects (social factors) affecting recycling behavior, especially through the prism of recycling photovoltaic panels. Research method-ology theorists distinguish two types of systematic literature review. The first touches on a research topic that is relatively mature and explored by numerous researchers and proposes a conceptual framework for the synthesis of knowledge in the indicated topic, while the second touches on areas that are only gaining popularity among researchers and have not yet been explored. Due to the fact that the researched area is an emerging topic, the research was carried out according to the second type of review [19].The review itself was conducted in five stages, in accordance with the best practices in this area, indicated by numerous researchers dealing with the methodology of literature reviews [20-29]. The first stage was to define the purpose of the research, as well as to indicate the knowledge repositories that will be used for research. The second step was to find scientific articles via ScienceDirect® using the following keywords (search by title, abstract or author-specified keywords): photovoltaic recycling (463 articles), photovoltaic waste (825 articles), photovoltaic social (656 articles), recycling social behavior (311), recycling social (1709). At this stage, no additional filters were applied (e.g. limited to a subject area). The next stage consisted in data extraction, i.e. capturing those articles that had the indicated keywords in the title and touched on areas that would allow the research to be carried out. In this way, 131 articles were selected, which were then subjected to a preliminary analysis, which allowed for the selection and analysis of the final number of articles that served the purpose of the research (98 articles on the recycling of photovoltaic panels, as well as social aspects of attitudes related to recycling in general, most often on at the level of individual consumers or households).

# 3. Results

Recycling is essential to the achievement of the Sustainable Development Goals [30], and as the human population continues to grow exponentially, so does the consumption of materials, which leads to even greater interest by governments and science in all aspects related to recycling. International efforts to assess waste management in general have resulted in numerous studies focusing on technological, contextual and psychological factors considered to be crucial in predicting behavior related to the recycling of household waste and industrial waste [31-36]. And just as there are numerous research works in the field of recycling photovoltaic panels, there is a clear research gap in the aspect of analyzing the social dimensions of recycling photovoltaic panels, as observed by Daniela-Abigail et al. 2022 [37] and as shown in Table 1 [38-57].

**Table 1.** *Meta-analysis of recycling aspects research*

| Research | Analysis of environmental impact | Analysis of economical aspects | Analysis of social aspects |
|---|---|---|---|
| Fthenakis (2004) | + | - | - |
| Fthenakis and Kim (2007) | + | - | - |
| Fthenakis, Kim and Alsema (2008) | + | - | - |
| Choi and Fthenakis (2010) | - | + | - |
| Cucchiella, D'Adamo and Rosa (2015) | - | + | - |
| Latunussa et al. (2016) | + | - | - |
| Tsang, Sonnemann and Bassani (2016) | + | - | - |
| Bogacka, Piko´n and Landrat (2017) | + | - | - |
| Vellini, Gambini and Prattella (2017) | + | - | - |
| Deng, Chang, Ouyang and Chong (2019) | - | + | - |
| Ardente, Latunussa and Blengini (2019) | + | - | - |
| Wang, Oguz, Jeong and Zhou (2019) | + | + | - |
| Liu, Zhang and Wang (2020) | - | + | - |
| Venkatachary, Samikannu, Murugesan, Dasari and Subramaniyam (2020) | + | + | - |
| Mahmoudi, Huda and Behnia (2020) | + | + | - |
| Grant, Garcia and Hicks (2020) | + | - | - |
| Fthenakis et al. (2020) | + | - | - |
| Chung, Seo, Lee and Kim (2021) | + | - | - |
| Tawalbeh et al. (2021) | + | - | - |
| Seo, Kim and Chung (2021) | + | - | - |

Due to the lack of research on the analysis of the social aspects of recycling photo-voltaic panels, an attempt was made to analyze the social aspects of recycling municipal waste, the production of which is about 2 billion tons per year [58], electronic waste and bulky waste, due to the fact that the vast majority of installations in the world are consumer installations (in terms of volume), they are most likely to pose the greatest potential risk in the case of a standardized recycling process. Since people are considered to be rationally important, it is believed that recycling behavior is shaped by determinants at various psychological levels and in terms of behavior at the community level in micro and brand terms [59], which is systematized in Table 2.

**Table 2.** *Meta-analysis of aspects influencing recycling behavior*

| Aspect | Explanation | Research |
|---|---|---|
| General knowledge | An increase in general knowledge leads to a change in attitudes, and then both attitude and knowledge ultimately influence the decision about whether and to what extent to perform a particular behavior | [60-61] |
| General knowledge about the environment | General knowledge about the natural environment is positively correlated with pro-ecological attitudes (including recycling) | [62-63] |
| Expertise | Both general knowledge (related to the broadly understood natural environment) and (above all) specialist knowledge in a given area (e.g. recycling) are important in changing behavior towards pro-recycling | [64-66] |
| Information provided in words | There is a correlation between verbal information on recycling and a change in attitude in this respect compared to information provided over the phone or via the Internet | [67] |
| Information campaigns | There is a correlation between increasing recycling behavior and environmental campaigns in the area | [68-70] |
| Use of social media | The use of social media in information campaigns at the level of the environment positively affects the activation of pro-environmental behavior | [71-74] |
| Pollution awareness | There is a correlation between pollution awareness and recycling activities | [75] |
| Education level | There is a correlation between the level of education and positive pro-ecological attitudes | [76-77] |
| Shopping habits | Shopping habits are correlated with attitudes towards recycling | [78] |

| | | |
|---|---|---|
| Behavioral habits from the past | Behavioral habits from the past translate into attitudes related to recycling | [79] |
| Social feedback (including social pressure) | Social feedback plays a role in increasing recycling behavior | [80-82] |
| Imitation | Imitation of observed behavior has a positive effect on the intensification of attitudes causing the intensification of recycling attitudes | [83-88] |
| Nostalgia | Nostalgia for the goods owned despite their lack of use can inhibit attitudes related to recycling | [89] |
| Emotions (fear, guilt, hope, pride) | Emotions have a positive impact on pro-ecological attitudes, including recycling | [90-94] |
| Awareness of the health aspect | The approach to recycling, as well as to health, positively affects the intensification of pro-ecological attitudes | [95] |
| Personality types | Personality type may imply behavior towards the natural environment and inhibit or intensify recycling attitudes | [96-98] |
| Personal standards | There is a correlation between personal standards and recycling behavior | [99-102] |
| Age, gender, education, income | Researchers do not agree on the direct correlation between age, gender, education and income and pro-environmental attitudes, because some indicate that such a relationship exists, while others that they have not noticed such a relationship | [103-110] |
| Reward and punishment | The use of the mechanism of reward and punishment may influence the intensification of pro-ecological attitudes | [111] |
| Effort related to the recycling process | There is a correlation between the required effort on the part of the consumer to recycle an item and the intensification of pro-ecological attitudes | [113-115] |
| Ethnicity | There is a correlation between ethnicity and pro-environmental attitudes (recycling) | [116-119] |
| Economic incentives | Economic incentives influence the intensification of pro-ecological attitudes, including recycling (depending on various factors, however, a positive impact can be observed) | [120-126] |
| Number of immigrants in a given area | A correlation was noticed between the number of immigrants in a given region and pro-environmental attitudes, i.e. in the case of immigrants from countries with a high percentage of pro-environmental attitudes, these behaviors had a positive impact on attitudes in a given area (imitation, social pressure) | [127-129] |
| Social heterogeneity | There is a correlation between social heterogeneity and positive pro-environmental attitudes | [130] |

While political, purely environmental or technical factors may seem important in controlling recycling behavior in a broad sense, psychological and social factors (such as those listed in Table 2) provide a more direct explanation for recycling behavior and can be a starting point in creating conditions for social control of behavior that has a direct impact on the environment, i.e. recycling process, especially the recycling of photovoltaic panels, which after a period of use can become a huge problem for individual consumers, especially those who do not have knowledge of the economic and ecological potential behind the reuse of materials from PV installations [131-132]. Environmental psychologists have been identifying predictors of environmental behavior for a long time, and the most frequently proposed model is the KAP (knowledge, attitude, practice) model [133-134], which was first applied in the field of family planning in the 1950s [135], but nowadays it is used in many social fields. It is characterized by, inter alia, cross-cultural comparability, ease of interpretation and versatility of implementation, and its basis is the foundation of public knowledge on the level of broadly understood environmental protection. It should also be emphasized that all the analyzed studies concern recycling in general, and not the recycling of photovoltaic panels, which, from the point of view of the potential effort on the part of the consumer with the installation, are much more engaging. Consequently, it can be concluded that, as in the case of recycling of consumer goods, including electronic goods (such as batteries, household appliances, accumulators, etc.), knowledge of the environmental impact of the elements of a photovoltaic installation after its use is key in the process of intensifying pro-recycling attitudes. Due to the fact that engaging in recycling activities brings both personal benefits (positive feelings and selffulfilment) and purely environmental benefits, it can also bring (significant) economic benefits (which can be a particular activating factor in the case of recycling of photovoltaic panels by consumers), it can be concluded that activities at the level of the photovoltaic panel recycling process should take into account not only purely technical, legislative or ecological aspects, but above all purely social issues, without which the others may be-come just empty concepts.

## 4. Conclusions and recommendations

The renewable energy sector, especially the photovoltaic sector, together with govern-ments and non-governmental organizations, should address the problem of recycling photovoltaic panels in individual countries, not when the problem occurs, but when the popularity of photovoltaic panels is increasing both among individual consumers and in industrial terms. Key recommendations include:

1. Development of regional and national policies that promote recycling attitudes at the level of photovoltaic panels, taking into account economic, ecological and social in-centives.
2. Development of infrastructure for the efficient process of recycling photovoltaic panels by individual consumers, due to the fact that the recycling process of photovoltaic panels in the case of industrial installations is much more developed, structured and logistically optimized.
3. Development and intensification of social campaigns, taking into account both traditional methods and individual meetings regarding the need and importance of recycling photovoltaic panels, as well as modern sources of communication (internet, especially social media, used by 3.81 billion in 2020 people [136]), aimed at increasing knowledge on the environmental impact of PV panels, and aimed at evoking specific emotions intensifying pro-recycling attitudes.
4. Analysing and using the social structure of a given region/country in order to optimize activities at the level of increasing social awareness in the context of recycling photovoltaic panels.

This publication can be a starting point for research in the field of social aspects related to the recycling of photovoltaic panels, and its aim was to structure and systematize knowledge in the field of social aspects related to the recycling of photovoltaic panels and recycling in general. The indicated aspects can be a signpost for the creation of strategies aimed at increasing the level of knowledge on the level of the need and importance of recycling photovoltaic panels and serve to create scenarios for positive control of social behavior at the level of recycling photovoltaic panels. Our analysis reveals

three critical gaps: (1) absence of empirical studies directly examining household behaviors regarding PV panel disposal; (2) lack of research on the role of installers and maintenance companies as intermediaries in the recycling process; (3) no studies examining the effectiveness of different communication strategies for PV recycling awareness. Unlike general waste recycling, PV panels require specialized handling and knowledge, suggesting that traditional recycling behavior models may need adaptation. Future research directions should include: (1) empirical studies examining actual recycling behaviors of PV panel owners using mixed-methods approaches combining surveys, interviews, and behavioral observations; (2) cross-cultural comparative studies to identify culture-specific factors influencing PV recycling attitudes; (3) longitudinal studies tracking changes in social attitudes as PV installations age; (4) experimental studies testing the effectiveness of different intervention strategies (educational campaigns, economic incentives, social pressure mechanisms) on PV recycling participation rates.

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