New approach to PV panel LCA evaluation

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ABSTRACT

PV panels are regarded as a very promising future source of energy. Their environmental performance seems to be excellent during the use phase. Unfortunately their production could create high environmental burden. Waste utilization phase could be harmful as well. The final score produced for the whole life cycle is mostly based on environmental impact of those two phases. This means that while trying to make PV panel more environmentally friendly, the special attention should be paid to evaluation and optimization of reduction environmental impact in those phases. We should remember that economic viability is important as well. The replacement of some substances by their equivalents could make the really important change in overall environmental performance of the product.

In order to perform environmental optimization well the special tool is needed. It should include all used materials and substances, their quantities, and environmental properties. Results should be produced in a clear form to make the better and more informed decision. The role and importance of environmental impact of development of new technology – which is usually omitted - should be noticed and underlined.

The framework of environmental impact evaluation of PV panels is presented in the manuscript. It could be used to make the optimization of final product from the environmental point of view. The role and importance of proper planning and technology phase development is discussed as well.

Comprehensive approach including implementation and development of the new technology is rarely presented in publications. This gap is filled by methodology presented in the manuscript. In addition, the manuscript contains wide variety of valuable data, which will determine the real impact of this case photovoltaic on the environment.

INTRODUCTION

The environmental impact of photovoltaic panels (PVs) is a fairly widely studied topic, generally performed using the Life Cycle Analysis (LCA) methodology. It is essential to have a clear view what is important in developing the technology of PV module. In the manuscript the evaluation based on the LCA approach is presented with strict definition of framework components of analysis, which should be done for each new technology. (Jinqing Peng, 2013)

The main disadvantage of photovoltaic cells was the fact that although they are supposed to have lower environmental impact in many cases building cells require much more energy than they are able to provide during the whole life cycle. However, in specific conditions PV cells could produce clean energy. Unfortunately in in global perspective, the balance could turn out to be negative. The analysis of PV cells production shows that the environmental impact is huge. Therefore, to comprehensively evaluate the problem it is proposed to use new evaluation scheme. In the manuscript this scheme is supported by the validation example which makes it possible to see the components and phases. This would make it possible to optimize details of technology to minimize negative impact of PVs while maintaining the economics added value. (Landrat, 2016)

Although most scientists agree with the statement that power engineering needs renewable sources of energy to meet the growing energy needs, it should be always kept in mind that the production of the new technology also could cause environmental impact (Alsema E., 2005). In the case of photovoltaic cells to produce a complete module we need a long list of chemical compounds as well as plastics, which have a negative impact on the environment. Their production should also be taken into account in a comprehensive analysis. The schematic environmental impact assessment containing assessment of technology creation is given in fig. 1.

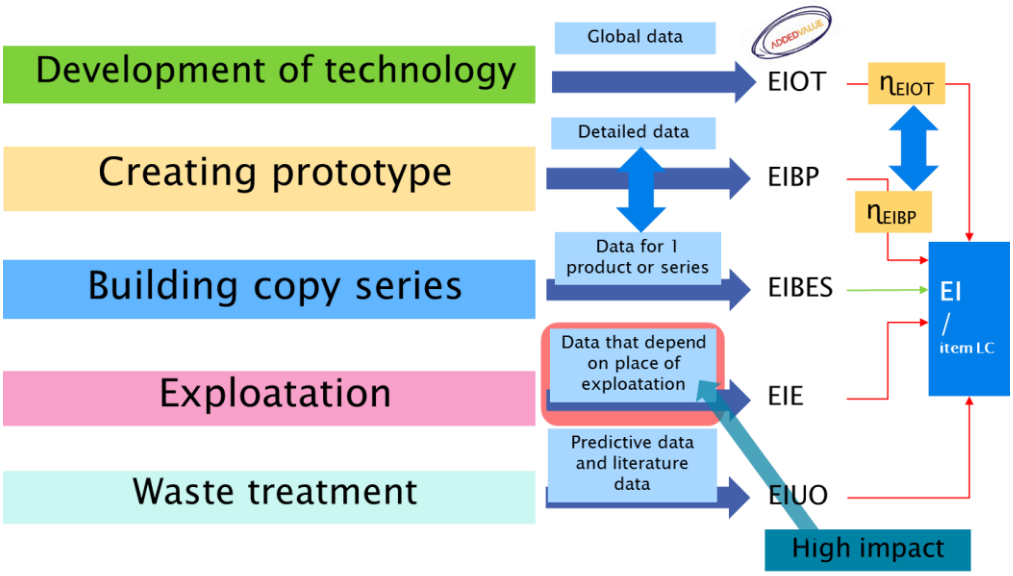

Fig. 1. Scheme of concept for LCA analysis of PV module in full life cycle

METHODOLOGY

New approach in LCA evaluation is presented in manuscript. Generally indicators and impact categories are based on ReCiPe methodology. ReCiPe is a methodology which connects the midpoint and the endpoint of the environmental analysis by using many categories of impact which are divided into groups. The most important feature of ReCiPe is its ability to transform a long list of LCI results into a limited number of indicators. These indicators represent a relative impact on natural environment. There are two levels of indicators in ReCiPe methodology. They are divided into eighteen midpoint and three endpoint indicators.
The eighteen midpoints are fairly accurate but hard to interpret. Three easy to understand but more general end categories are: Human Health, Ecosystems and Resources.

The method allows to choose between types of indicators and facilitates the process of correct interpretation. The advantage of this method is the ability to deliver one environmental indicator based on implementing midpoint indicators. Individual weights for particular categories are implemented in the software which is used as an analytic tool, e.g. SimaPro. Weights can be modified if the importance of particular categories of environmental impact changes. Weighting process is transforming the value of indicators into numeric parameters by assigning a certain amount of points to each category of impact. A unifying unit is the midpoint (Pt). It is the measure of environmental impact that one European has within one year.

The final results of environmental impact assessment should include three types of results: comprehensive analysis of the environmental impact of the proposed solutions, the proposal of process optimization in order to minimize the negative impact on the environment and the practical effect which would show the effect of environmental innovations introduced in comparison to other solutions of this type.
The general goal of each production of PVs should aim at the lowest possible environmental impact of developed technology. According to equations 1 and 2, environmental indicators should be as small as possible.

$$\mathrm{TEI} = \sum_{i=1}^{n}(TEI_i) \rightarrow \mathrm{min} \tag{1}$$

$$TEI_i = EI_i \cdot m_i \tag{2}$$

where:

TEI – total environmental impact
n – product or process of full part of LCA analysis
i – substances forming part of a product or process
EI_i – environmental impact of item under analysis i
m_i – measure of substance i (mass or energy unit)

The analysis should include all material and substances used for production as well as energy used. In order to perform properly designed environmental evaluation, individual data of the environmental impact of each substance and for a global process should be supplied. Data used comes usually form databases eg. Eco-invent.

In order to decide which element makes the highest environmental burden it is essential to include both the quantity of the substance and its environmental properties. This information will be important for future optimization of the final product. The methodology which is widely accepted is ReCipe.
To make the picture more clear the potential environmental risk (ζ) was introduced. This would be the measure of environmental importance of particular substance. It is defined by following equation:

$$\boldsymbol{\zeta} = \frac{TEI_i}{TEI} \cdot 100\% \tag{3}$$

The results could be presented in a clear form as shown in table 1.

Table 1. Example of the environmental analysis with environmental risk presentation.

Substance i	EI_i (Pt/kg)	m_i (kg/FU)	TEI_i (Pt/FU)	ζ (%)
Substance 1	A	B	A*B	X%
…				

The proposed scale of the potential negative impact is shown in Table 2. Referring to table 1 and 2, the symbols represent $\boldsymbol{\zeta}$ - potential environmental risk, FU – functional unit (depending on the analysis of the functional unit can be defined as a particular product or process or technology), Pt – environmental points.

Table 2. Scale of potential environmental risk

ζ	0-3%	4-10%	11-30%	31-70%	71-100%
Potential environmental risk	Very low	Low	Medium	High	Very high
Scale	1	2	3	4	5

The proposed guidelines evaluates the negative impact of the main substances that are part of the technology or product. It happens that the replacement of the components with the highest potential ζ is simple and only requires the replacement with the equivalent, which can have a much lower rate or mass needed for production. Globally we should always have to go towards minimizing the negative impact on the environment. We should remember that the potential environmental risk is created for specific processes. In order to tell something about environmental impact of every substance in global meaning, we must take the results of LCA analysis in the environmental unit.

LCA ANALYSIS OF NEW TECHNOLOGY DEVELOPMENT

In order to make the analysis complete, it must include the environmental impact of the production process. In the case of photovoltaic cells, this is particularly important because, analysing the process of exploitation only, the environmental impact is small. However, taking into account the production process, and all harmful substances used, the high environmental impact of PV panel could arise. The exploitation stage in full life cycle is much more environmentally friendly, but not totally. However, before a new product or technology appears on the market, the long process of tests, trials, production of prototypes, while a lot of substances are used, co-products and energy resources which are used. This could make the environmental impact quite high. There are various chemicals and their potential impact on the environment can be enormous. Often this is not taken into account, even if it sometimes goes hand in hand with the economic analysis. Inventory of data of all materials, energy and chemicals that are when creating new technologies is needed. This will help to see if the environmental impact of introducing a new technology will be offset by the environmental relief that will be implemented by the new product or method of production. The idea of such data sharing in LCA analysis was introduced in a project that is being led at Silesian University of Technology. The goal of this project is to create an innovative photovoltaic car body isothermal and cooling.

The project includes the implementation of the new car bodies which are equipped with photovoltaic modules with support in the form of Luminescent Solar Concentrator - LSC. This cover has the function of structural box construction and allows the acquisition of clean, renewable solar energy. In addition, it reduces the energy generated with the fuel and reduces the amount of exhaust gas and the emissions generated. PV solar modules constituting the car body are produced using a newly developed single-link flexible solar cells and silicon cells at the edge of the construction, which due to its parameters are preferred for use in photovoltaic systems with concentrators as well as conventional silicon cells.

The most difficult thing is to collect comprehensive data due to large number of producers and the confidentiality of data. The data collected successively are great added value for the assessment of the environmental effects of the project. Further steps are the implementation and evaluation of designed path.

Table 3 presents the results of the LCA analysis of development of technology for the photovoltaic car body isothermal and cooling project. The development of the technology is divided into 6 different processes:

1. Development of PMMA surface hardening technology
2. Development of lamination technology
3. Development of edge mirror manufacturing technology on PMMA
4. Development of diffusion technology for LSC (luminescent solar concentrator) and EVA foil
5. Development of the cells production technology
6. Additional (global) substances for all processes

Table 3. Results of LCA evaluation of new technology development

Processes j	**TEI_j (kPt/FU)**	**ζ (%)**	**Potential environmental risk**
Development of PMMA surface hardening technology	0,0947	4,65	Low
Development of lamination technology	0,8486	41,71	High
Development of edge mirror manufacturing technology on PMMA	0,0007	0,03	Very low
Development of diffusion technology for LSC and EVA foil	0,8466	41,61	High
Development of cells produce technology	0,2195	10,79	Low/Medium
Additional (global) substances	0,0246	1,21	Low

The results for the stage of development of technology shows that the highest environmental impact is for development of lamination technology and development of diffusion technology for the LSC and EVA foil. These processes give more than 80% of total impact. Other processes in this case can be considered as less harmful. The further analysis of the impact of individual processes, the results of the environmental impact of individual substances are presented in tables 4 and 5.

Table 4. Results of LCA analysis of development of lamination technology

Substances i	**TEI_i (kPt/technology)**	**ζ (%)**	**Potential environmental risk**
Polymethyl methacrylate, sheet	0,1174	13,86	Medium
Ethylvinylacetate, foil	0,0368	4,35	Low
Toluene, liquid	0,0020	0,23	Very low
Electricity, low voltage {PL}	0,6904	81,55	Very high

In case of development of lamination technology and development of diffusion technology for the LSC and EVA foil, the highest impact on the environment in the whole process delivers electricity. In the case of development of lamination technology the rate is 81.55% of the total impact of this process. The environmental impact score is 0.6904 kPt / technology. For the development of diffusion technology for LSC and EVA foil the rate linked with electricity is 64.57% of the total impact of the process. However, the environmental impact is close to the previous one and amounts to 0.5480 kPt. Because the analysis includes real data, the environmental indicator for electricity has been chosen for the Polish mix. In this case, in order to reduce the negative environmental impact of the processes, one should reduce energy consumption and then the source of energy with less environmental impact should be selected. As the Polish mix is mainly based on coal, so replacing it with, for example energy from other, cleaner sources would give a positive result.

Analysing the next substances in both cases, the negative impact on the environment have Polymethyl methacrylate sheet. In the case of development of lamination technology rate is 13.86% of the total impact of process and environmental rate is 0.11774 kPt / technology. In the case of development of diffusion technology for LSC and EVA foil rate is 22.31% of total impact of process and environmental rate is 0.1893 kPt / technology.

Another substance which is part of the lamination process is Ethylvinylacetate, foil, the result of which is 4.35% of the total effect, and 0.0368 kPt. That impact should not be underestimated, because of its value on the level of 36.8 Pt, which can be attributed to the production of approximately 100 kWh of electricity from coal in Poland (Ecoinvent). In case of the process of diffusion technology for LSC and EVA foil, substances that have a significant impact is methanol (5.66%), Palmitic acid (3.83%).

This evaluation can be applied both globally for the entire LCA analysis of the technology and for the selected analysis area. Results could be easily presented and the substances or fuels / energy that cause the most harm could be chosen. Basing on such analysis as well as on sensitivity analysis, environmental guidelines for process design can be developed.

If we are working on reducing the environmental impact of a specific process, percentages can give you information in a very simple and easy to understand way. However, it should always be borne in mind that the results of environmental indicators should be compared in the relevant unit to answer the question whether the impact of chemicals has a negligible effect. It may be that in the case of the analysed process the impact of the substance does not matter, but by comparison with a similar process the indicator may turn out to be huge. Therefore, always you need to analyse the results on many levels and use common sense when assessing environmental aspects.

Table 5. Results of LCA analysis of
development of diffusion technology for LSC and EVA foil

Substances i	**TEI_i (kPt/technology)**	**ζ (%)**	**Potential environmental risk**
Polymethyl methacrylate, sheet	0,1893	22,31	Medium
Methanol	0,0480	5,66	Low
Palmitic acid	0,0325	3,83	Low
Coconut oil	0,0089	1,05	Very low
Maleic anhydride	0,0002	0,02	Very low
Polycarboxylates	0,0025	0,30	Very low
Adipic acid	0,0008	0,09	Very low
Toluene, liquid	0,0157	1,86	Very low
Ethylene	0,0000	0,00	Very low
Tetrahydrofuran	0,0005	0,06	Very low
Glycerine	0,0000	0,00	Very low
Triethanolamine	0,0022	0,26	Very low
Electricity, low voltage	0,5480	64,57	High

On the basis of evaluation made for the technology development, shown on the fig. 2 and 3, it is possible to indicate elements which have the highest influence on final score. This makes possible to make more informed decision making process. In case of individual preferences related to importance of different impact categories it is possible to make replacements of specific substances or material having crucial influence on the final score. This would make the whole process of designing more environmentally oriented. Finally products could have better environmental performance.

The possibilities of using methodology and impact categories is shown on figure 3. Some analysis are made for specific needs, then the above mentioned technology can be presented for the chosen impact category that we are interested in. You can also observe what is importance of specific areas. Fig. 2 summarizes all the information and indicates the 3 main categories that can also be used to evaluate processes for their harmfulness, eg for humans.

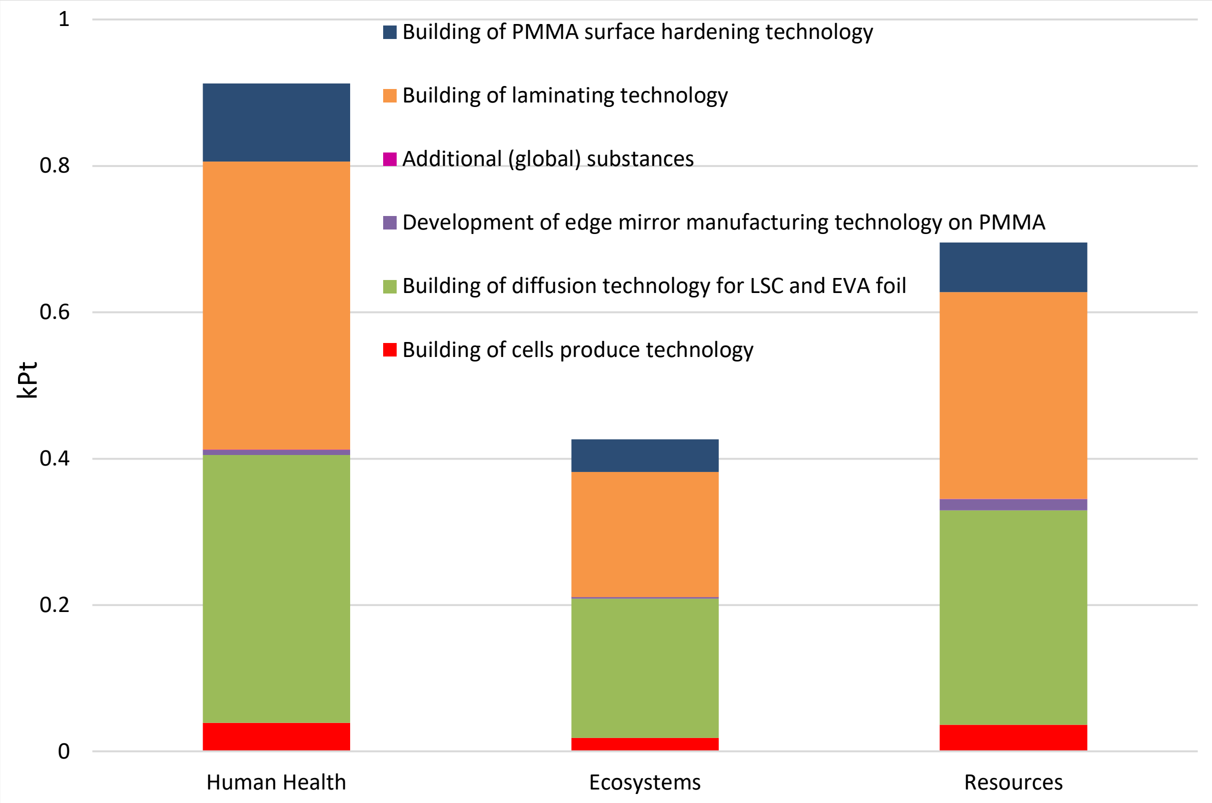

Fig. 2. Distribution of environmental impact in 3 main impact categories for development of new technology.

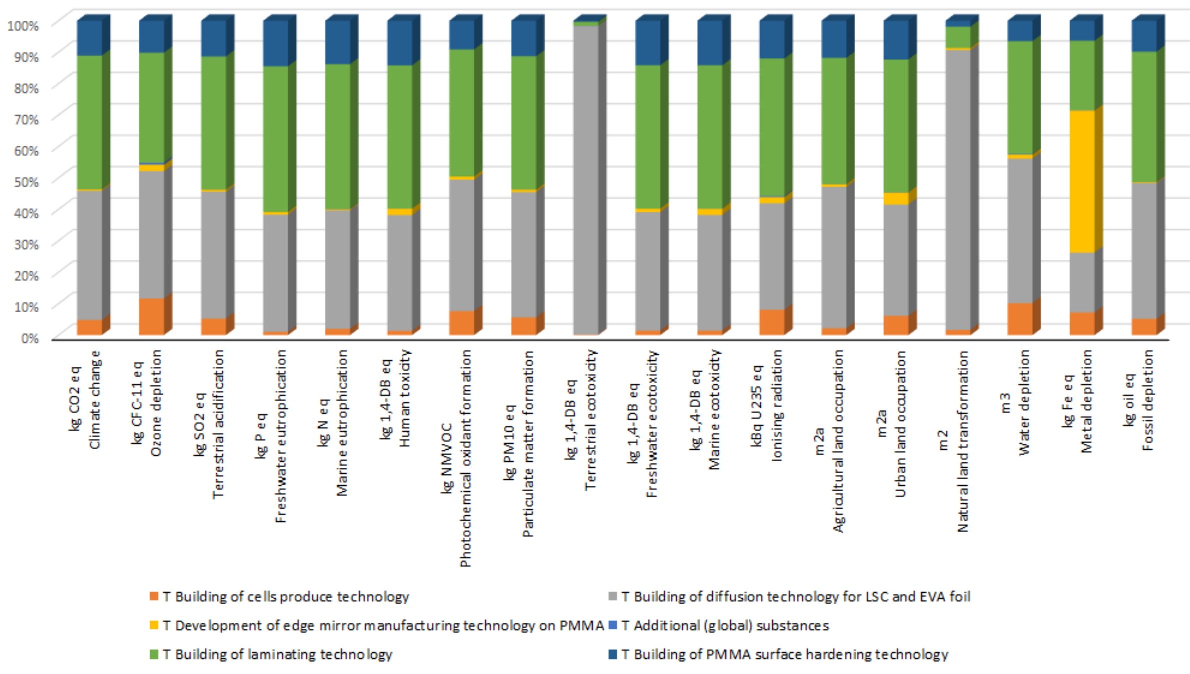

Fig. 3. Distribution of environmental impact in different impact categories for development of new technology.

LCA ANALYSIS OF PROTOTYPE CREATION

The next step in the proposed LCA analysis approach it is the analysis of creating of the prototype. Table 6 shows the results for one of several prototypes created during the project. In case of prototype, it can be observed that the distribution of harmfulness of individual substances is more stratified than in case development of technology. In this case, we do not have electricity, because it is measured globally for all sub-processes. Nevertheless, such an arrangement makes it possible to reduce toxicity by replacing some other components or to reduce the probe mass. Figure 4 shows the results of the analysis divided into 3 main categories. In case of development of technology, the highest impact observed in the category of human health. However, in case of prototype analysis, the highest impact is observed in Resources category. The main reason is the use of silicon.

Table 6. Results of LCA analysis of creating prototype

Substances i	**TEI_i (kPt/technology)**	**ζ (%)**	**Potential environmental risk**
Polymethyl methacrylate, sheet	0,0273	29,25	Medium/High
Ethylvinylacetate, foil	0,0005	0,48	Very Low
Polystyrene foam	0,0065	6,93	Low
Silicone product	0,0020	2,16	Very low
Polyurethane, flexible foam	0,0077	8,23	Low
Glazing, double	0,0377	40,34	High
Photovoltaic cell, multi-Si wafer	0,0118	12,60	Medium

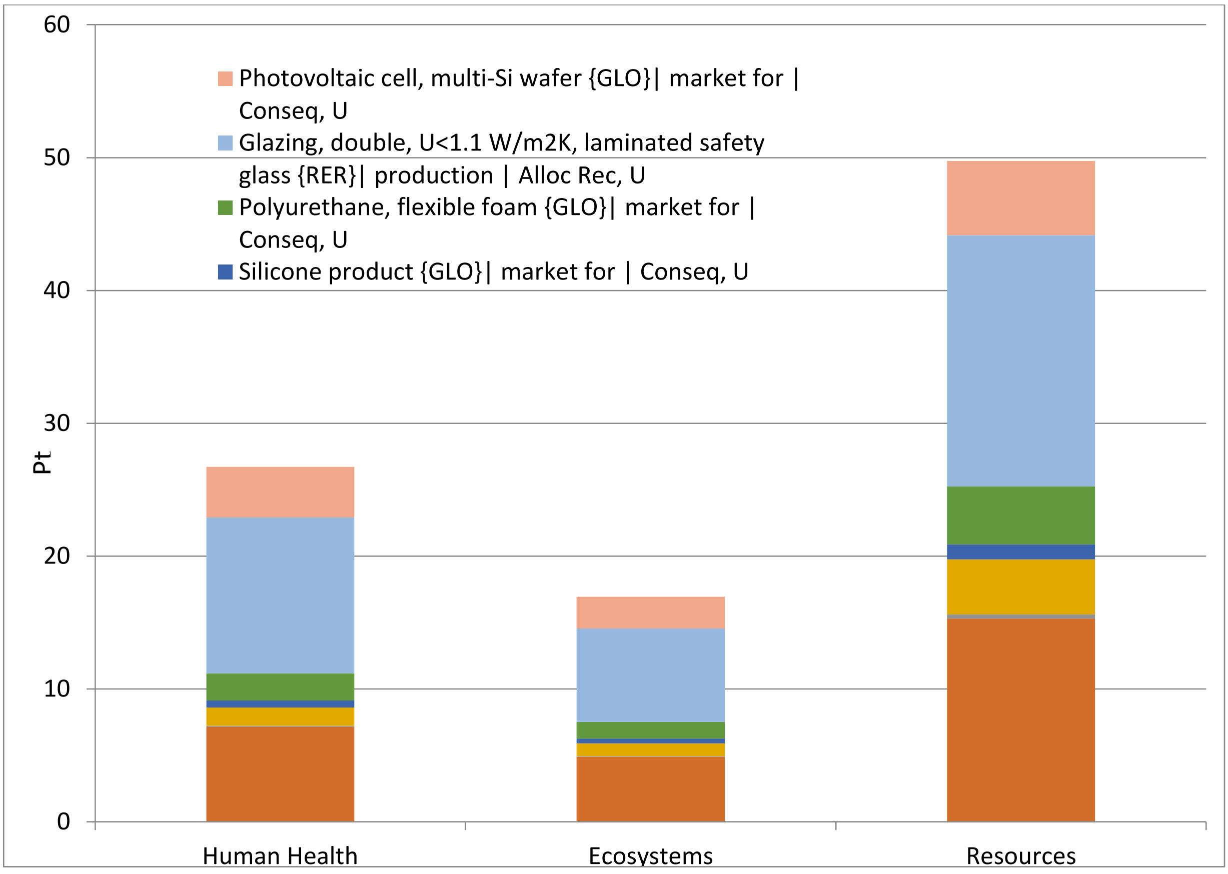

Fig. 4. Distribution of environmental impact in 3 main impact categories for prototype.

COMPARISON

On the basis of evaluations performed in the projects and presented in the manuscript the comparison of environmental impact for creation of prototype and development of technology could be made. The result of this comparison is shown in Table 7. The environmental impact of creating of prototype is approximately 4.6% of the environmental impact development of technology. However, it should be remembered that data is about creating one prototype. During the project was created 5 prototypes. The next step is to translate these experiences to the serial model. Then investigation of the efficiency in the exploitation phase is needed as well as to examine the environmental impact of the waste phase. Such comprehensive data should be collected for each product.

Table 7. Comparison of results of creating prototype and development technology

Stage	TEI_{stage} (kPt/technology)
Development of technology	2,0347
Creating of prototype	0,0934

CONCLUSION

The research presented in the manuscript is an element for assessing the environmental effects that was created within a technology development project and creating environmental guidelines for optimizing the environmental effects of its implementation.

All steps of LCA analysis should be described in a clear manner. Breaking up into individual performance indicators gives the opportunity to perform a quick EI evaluation. The presented methodology can indicate which substance or process has the most important environmental impact. This allows to analysis what actions need to be taken to minimize the negative impact on the environment in the best possible way.

This could help to avoid the situation when we try to minimize the amount of a substance that cannot significantly affect the environment. It cannot be forgotten that the impact is calculated in relation to the sum of all analyses. It could happen that a component that has small impact on the environment generally has a huge impact in the particular process comparing to other competing process. In order to avoid such situations, the results of the environmental analysis should be analysis in accordance with the ISO 14040 guidelines and using the approach presented in the manuscript.

In addition, this way of presenting results can be compared with economic analysis. This can create an economic and environmental indicator that can be used by decision makers who care about the environment but at the same time are focused on the economic efficiency.

The methodology presented in the manuscript could be used in order to make the optimization of environmental impact of PV panels during the manufacturing process. The research emphasise value and importance of the technology development and its environmental impact that could be not negligible.

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