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The Influence of Selected Factors on PV Systems Environmental Indicators

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1. Introduction

Since the Brundtland Report (1987), an increasing attention is applied to the issue of the need to ensure sustainable development of societies. This should be done through the creation of such components of the development of civilization, so that the future generations can benefit the same environmental resources, as the current generation can. Implementation of this concept requires such methods of rational use of the qualities of the environment, which do not disturb the balance in the relations between environment, society and economy.

Energy is now a key element necessary for economic and social development, as well as for raising the living standards of people (Liu 2015, Chakraborty et al. 2016, Sztumski 2016, Kowalska et al. 2016). In relation to the companies producing heat and electricity, sustainable development means compliance with the permitted standards and respect for ecological and specific local conditions in determining the direction of development. The energy industry is in this case essential due to the fact that from 1960 to 2000, the primary energy consumption has increased by over 320% while the world population grew up twice. According to the subsequent forecasts, this demand will continue to grow, which will result in a number of negative effects, such as the depletion of mineral resources, further increase of the concentration of carbon dioxide in the atmosphere (Grudziński & Stala-Szlugaj 2015) and pollution of the environment by the mining industry.

The proposals for the future of energy tend to invest in new, environmentally friendly technologies, including renewable energy sources (Czechowska-Kosacka 2012, 2013, Jarzyna et al. 2014, Żelazna, Gołębiowska 2015, Uliasz-Bocheńczyk & Mokrzycki 2015). One of the popular technologies for recovery of energy from renewable sources is the installation of photovoltaic panels. With regard to the electricity produced in the photovoltaic conversion of solar energy, its development has entered a phase of rapid growth. However (due to the fact that the processes of production facilities for the conversion of solar energy, as well as the need for their maintenance and final disposal is associated with consumption of raw materials, including rare elements and emissions), solar technologies are sometimes referred to as environmentally and economically inefficient.

The literature studies on PV systems analysis show that the highest emphasis is put on the issues of greenhouse gases emission and energy payback time (Frankl 2004, Fthenakis 2004, Fthenakis et al. 2008). The selected results of LCA studies are presented in Table 1.

Table 1. The comparison of LCA results for PV systems
Tabela 1. Porównanie wyników analiz LCA dla systemów fotowoltaicznych

Author	Type of cell	GHG emission (g CO_{2eq}/kWh)
Asdrubali et al. 2015	various (review)	9.4-197
Hou et al. 2016	c-Si	60.1-81.3
Ito et al. 2003	multi-Si	12
Ito et al. 2016	CdTe	27.4-38
Jungbluth 2005	multi-Si	39-110
Kabakian et al. 2016	mono-Si	38.9-40.2
Kannan 2006	mono-Si	165
Pacca 2007	multi-Si	72.4

The presented results vary significantly because of the different system locations, types, and sizes. Moreover, the GHG emission is the only parameter taken into account, which does not incorporate the burdens connected with emission of heavy metals, consumption of resources, etc. Therefore, the aim of this research work is to determine the environmental impact of the various life stages of solar systems based on thermal and photovoltaic conversion of solar energy, working in the four selected climatic conditions (Spain, Switzerland, Poland, Lithuania), on the basis of Ecoindicator and GHG emission. The research work includes the Life Cycle Assessment of energy systems used in individual housing, both on-grid and off-grid systems.

2. Methods

The research method used in this study is based on environmental Life Cycle Assessment based on material, energy, waste and emission balance. The methodology for the analysis of the final results of a inventory includes:

- Ecoindicator'99 as a measure of damage to individual elements of the environment,
- Global Warming Potential 100a according to the International Panel on Climate Change as a measure of the impact of global climate change.

EcoIndicator'99 is the method used for evaluating of environmental effects in the life cycle perspective. Ecoindicator'99 simplifies the categories of damage to the three basic: Human Health, Ecosystem Quality, Resources (Kowalski et al. 2007). At the same time, this method distinguishes eleven impact categories.

Calculation of Ecoindicator is based on the list of emissions into the environment and resources consumed in relation to certain patterns. The damage function shows the relationship between the impact of a product or process on the environment in relation to human health, ecosystem quality and natural resource reduction (www.pre.nl 2014). The final result is expressed as single score (Pt).

Global Warming Potential method provides a quantitative assessment of the potential of greenhouse effect creation. The calculations are carried out for selected time horizon (the recommended perspective used in this paper is 100 years). Basic substance expressing the environmental impact of this category is carbon dioxide, for which parameter of characterization equals GWP = 1. In this technique, substances like CO_2, CO, N_2O, SF_6, CH_4 and certain halons and CFCs are taken into account (Żelazna, Pawłowski 2011).

Life Cycle Impact Assessment method GWP 100a is based on the procedure of characterization of the emission into the atmosphere on the basis of the list of parameters.

As the functional unit, 1 kWh of generated electricity was used in the study. The system boundaries include processes of production of panels and equipment, service and utilization of the installation after the time span 30 years. The collection of data for inventory was based on Ecoinvent database and computer simulation of installation work. The analyzed installation were designed with nominal power of 4.5 kWp. The analyzed parameters influencing the final results are:

- location,
- type of panels installed (a-Si, multi-Si),
- type of installation (on-grid, off-grid).

3. Results

As the result of inventory and impact assessment, the shares of analyzed unit processes in the system life cycle were presented. As can be noticed in Fig. 1., the production of solar panel has the highest contribution in the final indicator calculated for the selected nominal power of installation (4.5 kWp). The other important processes include servicing and batteries use in off-grid installations. Installation of the system, with smaller impact, includes the components needed for panel foundation. Production of cables and transportation of the system components are not the major processes, since their shares in final result are negligible.

The impact category Fossil fuels is the leading in each analyzed system, as well as the Respiratory Inorganics. Both of the mentioned categories are strictly connected with the energy generation based on fossil fuels, with emission of particulate matter, sulphur and nitrogen oxides, etc. The contribution of Fossil fuels category exceeds 50% in the case of off-grid multi-Si system, where the energy consumption is the highest (processes of crystalline Si production and battery production).

Amorphous silicon technology is less energy consuming, therefore the contribution of Fossil fuels equals ~40%. The another important categories are Minerals (including silicone production from quartz sand, as well as metals necessary for the base and frame production), as shown at the Figure 1.

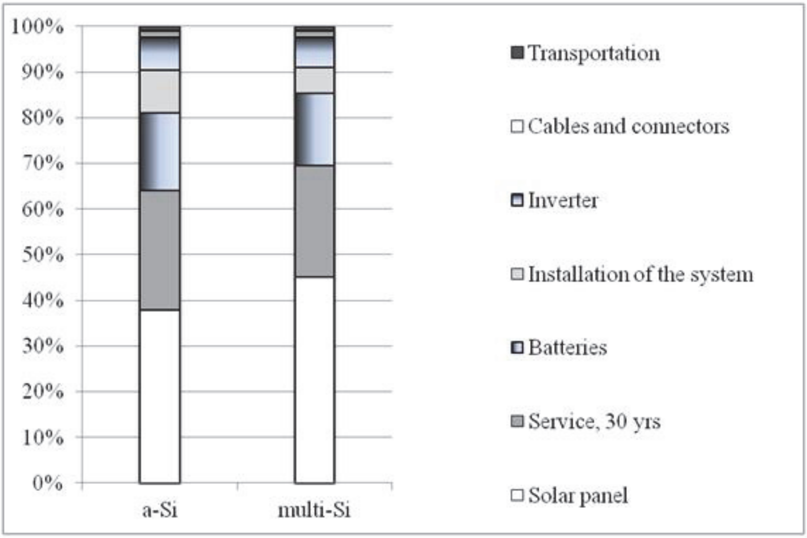

Fig. 1. The contribution of the analyzed unit processes in final Ecoindicator result (single score) calculated for a-Si and muli-Si based installations
Rys. 1. Udział analizowanych procesów jednostkowych w wartości wskaźnika pojedynczego obliczonego dla instalacji z panelami a-Si i multi-Si

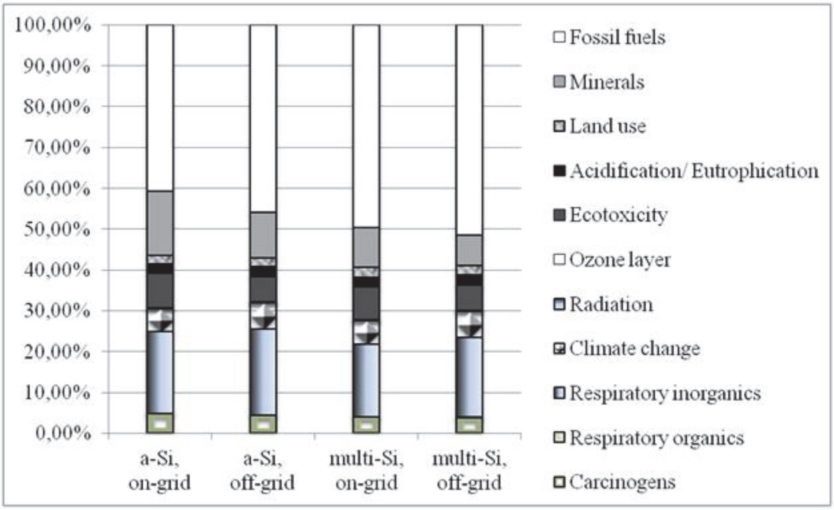

Fig. 2. The contribution of the impact categories in final Ecoindicator result (single score) calculated for a-Si and muli-Si based installations
Rys. 2. Udział kategorii wpływu w wartości wskaźnika pojedynczego obliczonego dla instalacji z panelami a-Si i multi-Si

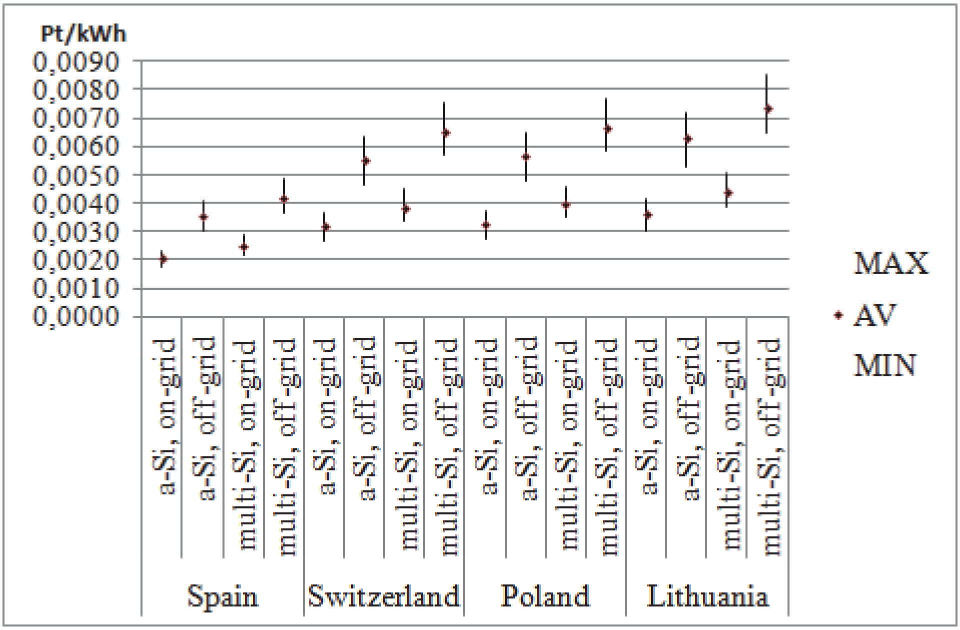

Fig. 3. Ecoindicator per functional unit (Pt/kWh) analyzed for selected locations of system

Rys. 3. Ekowskaźnik na jednostkę funkcjonalną (Pt/kWh) dla wybranych lokalizacji instalacji

In the interpretation of the final results, related to functional unit (Pt/kWh), the location of system was taken into account (Fig. 3). The most important issue is prognosis of system energy generation. In favorable climatic conditions, like Spain, the final Ecoindicator per functional unit vary from 0.002 Pt/kWh for on-grid, a-Si system to 0.0042 Pt/kWh for off-grid, multi-Si system, while in Lithuania it rises to 0.0043 Pt/kWh and 0.0072 Pt/kWh respectively. The another important issue is the energy balance of the analyzed countries and the comparison between PV and conventional energy indicators. According to the recent studies (Asdrubali et al. 2015), the possible environmental benefits from PV systems equal about 90% of reduction of emissions from energy sector; however, as was shown on the above graph, this issue should be considered separately for every location.

The error bars presented in Figure 3 depend on both possible energy gains estimation inaccuracy (± 3%), as well as the Ecoindicator uncertainty, calculated separately for each technology. The error bars express possible results variation depending on the input data; it is worth to notice that the ranges of common result for different technologies are small in the comparison with total range of error. Therefore, the results of this study may be treated as the base for comparison between analyzed technologies.

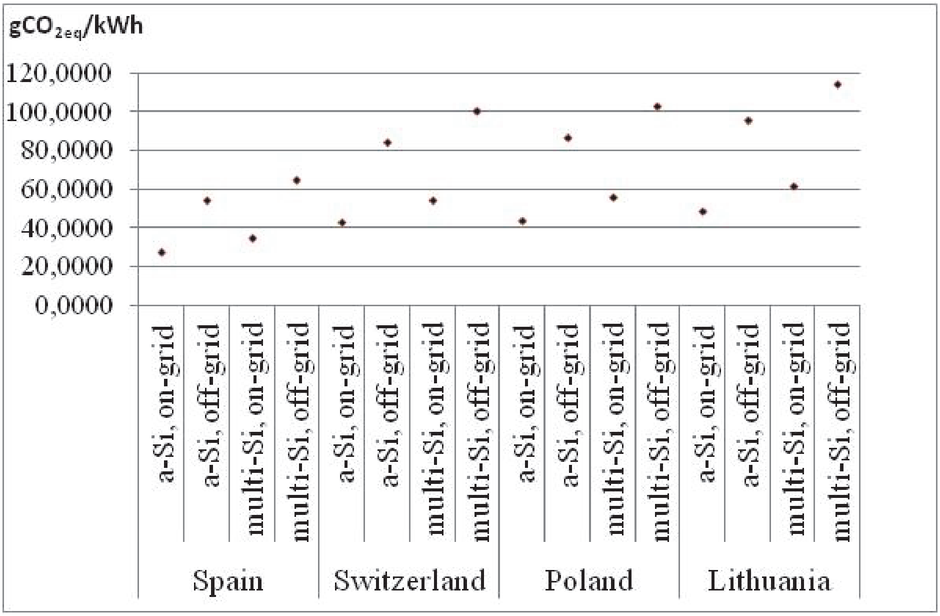

Fig. 4. Global Warming Potential per functional unit (g CO_{2eq}/kWh) analyzed for selected locations of system

Rys. 4. Wskaźnik emisji gazow cieplarnianych na jednostkę funkcjonalną (gCO_{2eq}/kWh) dla wybranych lokalizacji instalacji

The analyze of GWP indicator (Fig. 4) shows that the location, type of cells and type of installation cause high variability of predicted greenhouse gas emission. Grid-connected installations have generally better efficiency and lower energy inputs for system production, therefore the differences between on-grid and off-grid system GHG indicator is quite high. The obtained results (28-117 g CO_{2eq}) are similar to the study carried by Junbluth (Jungbluth et al. 2005) due to the similar analyzed climate conditions and size of the system.

4. Conclusions

With regard to the analyzed photovoltaic installations, the following conclusions were stated:

1. Reduction of the environmental burdens at the stage of photovoltaic cells production, as well as further technological developments in this field while reducing the energy input and re-use of components may help to reduce the impact on the environment,
2. The element of greatest importance to the potential environmental impact expressed as Ecoindicator is the production of photovoltaic panels. Reduction of the impact at this stage can have significant impact on the final size of the index, also due to the almost maintenance-free operation of the plant. The implementation of thin-film technology and work on improving their efficiency can bring the expected reduction of negative impact on the environment and human health,
3. Systems connected to the grid (on-grid systems) have a lower impact on the environment in relation to the off-grid installations due to the lack of batteries, which are the part of a significant share in the value of the calculated indicators for the installation. On the other hand, the batteries reduce the final efficiency of energy generation, worsening the final result of indicator calculated for functional unit,
4. An important factor in assessing the life cycle of photovoltaic systems is the size of the yield. Therefore the location of a system is a very important factor, which differentiates the results for selected European PV systems in the range of over 300%,
5. The use of life cycle assessment in the case of energy systems aims at broadening the knowledge of their users and potential investors on the chosen technology. This leads to decisions about replacing conventional technologies with modern, environmentally friendly solutions, and thus reducing emissions of pollutants into the environment and reducing the level of consumption of fossil fuels. These are important issues not only from an environmental perspective, but also for the health and quality of people life.

The future studies planned for the PV system will discuss the energy balance differences between the countries, as well as the newest technological solutions. The results of this study are expected to provide useful information to enact reasonable policies and development targets.

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Wpływ wybranych czynników na wskaźniki oddziaływania na środowisko instalacji fotowoltaicznych

Streszczenie

Rosnąca świadomość zagrożeń dla środowiska naturalnego i klimatu powodowanych przez działalność człowieka stała się motorem zmian w sposobie eksploatacji zasobów naturalnych. Wiele porozumień międzynarodowych, począwszy od Deklaracji podsumowującej konferencję Narodów Zjednoczonych z 1972 roku, a skończywszy na Porozumieniu Paryskim (2015) zostało podpisanych w celu minimalizacji negatywnego oddziaływania na środowisko, związanego w szczególności z energetyką. Jednym z podstawowych celów stawianych przed tą branżą jest spełnienie kryteriów rozwoju zrównoważonego. Instalacje fotowoltaiczne są jednym z odnawialnych źródeł energii, dotowanym z budżetu organizacji międzynarodowych oraz poszczególnych państw jako zmniejszające potencjalne oddziaływanie sektora energetycznego na środowisko. Jednakże produkcja, użytkowanie i zagospodarowanie końcowe modułów fotowoltaicznych nie są obojętne dla środowiska, istnieje więc konieczność porównania pozytywnych i negatywnych efektów powodowanych przez wymienione procesy. Bilans środowiskowy tego rodzaju instalacji może zostać oceniony za pomocą Oceny Cyklu Życia (Life Cycle Assessment). Celem pracy jest porównanie aspektów środowiskowych wybranych systemów fotowoltaicznych pracujących w różnych lokalizacjach.

Słowa kluczowe:
instalacje fotowoltaiczne, wskaźniki środowiskowe, Ocena Cyklu Życia, ekowskaźnik, gazy cieplarniane

Keywords:
photovoltaic systems, environmental indicators, Life Cycle Assessment, Ecoindicator'99, GHG