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# Greenhouse gas emissions in the life cycle assessment of photovoltaic systems

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*Abstract* — **Topic of the paper is analysis of greenhouse gas emission which is a very important indicator in the life-cycle of photovoltaic systems. The use of photovoltaic systems mitigates the greenhouse gas emission in comparison to the use of fossil fuels to produce electricity. The presented results are from the countries with developed photovoltaic industries regardless of the country potential of solar irradiation. Based on this parameter the development of photovoltaic systems in the region is enabled, because the Republic of Serbia has a great potential for using the solar energy. By comparative analyses of different types of photovoltaic systems the performances related to the greenhouse gas emission are obtained, and based on that, the selection of the optimal system can be done. Use of different energy mixes in photovoltaic systems production has a greater impact on the emission of $CO_2$. It is important to consider each indicator of the life-cycle analysis so the results would be complete.**

***Keywords – renewable energy; life cycle assessment; greenhouse gas emission, photovoltaic systems; comparative analyses.***

## I. INTRODUCTION

Use of renewable energies is a necessity nowadays because it contributes to the preservation of fossil fuels – non-renewable energy resources (natural gas, coal, oil) and improves the impact on the environment. Sustainable energy supply is also provided, and related to this, the systems for its use have to be developed.

Photovoltaic technology is one of the finest ways to use the solar power [1]. The Sun, as an alternative energy resource, allows the conversion of solar energy into electricity through photovoltaic systems. They consist of photovoltaic modules and balance-of-system components [2]. Use of the life-cycle assessment enables the selection of the optimal system between different types of photovoltaic systems related to a rational choice of energy supply systems and their impact on the environment [3]. In this paper, the greenhouse gas emission is analyzed. It is the main indicator in the life cycle assessment, beside the energy payback time. The ecological footprint is described by quantifying the entire greenhouse gases released during the lifespan of the photovoltaic system and it is expressed in carbon dioxide ($CO_2$) equivalents per kWh. In comparison with the emissions attributed to fossil energies, it is important to determine the environmental gain expected by the reduction of greenhouse gases related to the operation of photovoltaic electricity.

Every day, technology advances and the performances of photovoltaic systems are improved, while the negative impact on the environment is mitigated and the prices of the systems are reduced. Based on the latest research results presented in the paper, the values of the certain region can be only predicted, and not calculated, because the use of electricity mix for the system production varies from county to country, as well as the potential of solar irradiation of specific region.

## II. LIFE CYCLE ASSESSMENT OF PHOTOVOLTAIC SYSTEMS

Life cycle assessment is defined as structured, comprehensive method of quantifying material and energy flows and their associated impact in the life-cycles of products (i.e. goods and services) [4]. The life-cycle of photovoltaic system starts from the extraction of raw materials and ends with the disposal or recycling and recovery of the PV components (Fig. 1).

Silicon is currently the most widely used material for solar cell design [5]. The mining of raw materials, for example, quartz sand for silicon photovoltaics, is followed by further processing and purification stages, to achieve the required high purities, which typically entails use of fossil fuels and a large amount of greenhouse gas emission. The raw materials also include those for encapsulations and balance-of-system (BOS) components, such as silica for glass, copper ore for cables, iron and zinc ores for mounting structures, etc [4]. Beside the manufacturing and installation stages, the transport of all materials and components has a negative impact on the environment related to greenhouse gas emission. The gases emission is negligible during the stage of operation, and it is significant to calculate overall savings in comparison with emissions attributed to fossil energies. At the end of the lifetime, photovoltaic systems are decommissioned and disposed with valuable pars and material recycled, by using different mixes of energies, resulting in greenhouse gas emission.

The life cycle analysis is an orderly process which analyzes the input / output impact of the photovoltaic industry from the “cradle to grave”, with the inputs referring to materials and

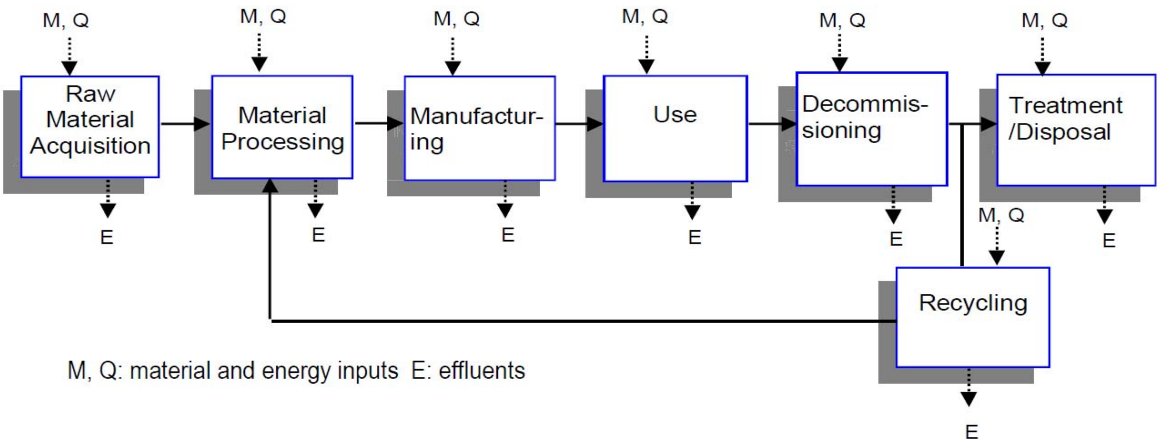

Figure 1. Flow of the life cycle stages: energy, materials and effluents for PV systems [4]

energy consumed and the outputs illustrated by greenhouse gas emissions and solid and liquid waste [6].

## III. GREENHOUSE GAS (GHG) EMISSIONS

### A. *Definition*

The greenhouse gas emissions during the life cycle stages of a photovoltaic system are estimated as an equivalent of carbon dioxide ($CO_2$) using an integrated time horizon of 100 years. The major emissions included as greenhouse gas emissions are: $CO_2$ (GWP = 1), $CH_4$ (GWP = 25), $N_2O$ (GWP = 298) and chlorofluorocarbons (GWP = 4750 - 14400) [4]. The global warming potential (GWP) depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime [7].

Reason why the greenhouse gas emissions equated with the emission of $CO_2$ is the largest contribution of this gas to the greenhouse effect from harmful gases in the mix (Tab. I) [7].

### B. *Direct and Indirect Emissions*

The overall greenhouse gas emissions consist of direct and indirect emissions. In the life cycle assessment of photovoltaic systems indirect emissions concern the overall energy, electricity included, needed to manufacture the units and direct emissions concern all of the chemical compounds, row materials included, which are involved in the manufacturing process and are a potential source of greenhouse gases [6].

### C. *Courently Available and the Latest Results*

Fig. 2 presents the greenhouse gas emissions per kWh generated for crystalline silicon and CdTe photovoltaic technologies and considers modules, frames and balance-of-system components, with an expected lifetime of 30 years. The results are estimates from the currently available in the public domain life cycle inventory data. The estimates are based on the Southern European irradiation of 1700 kWh/m$^2$/yr, and performance ratio of 0.75 [4].

TABLE I. GASSES RANKING BY THEIR DIRECT CONTRIBUTION TO THE GREENHOUSE EFFECT [7]

| Gas | Formula | Contribution (%) |
|---|---|---|
| Water vapor | H2O | 36 – 72 |
| Carbon dioxide | CO2 | 9 – 26 |
| Methane | CH4 | 4 – 9 |
| Ozone | O3 | 3 – 7 |

For mono-Si and multi-Si photovoltaic technologies the data describe wafers with 270 and 240 µm thicknesses, respectively. The estimate for CdTe systems is an average of two studies based on data from the First Solar's plant in Frankfurt-Oder, Germany. The ribbon-Si estimates were taken from the latest comparison lacking verified data.

Fig. 3 shows the latest greenhouse gas emissions of the major commercial photovoltaic technologies, but the data corresponding to the new mono-Si and multi-Si systems are not in the public domain. The poly silicon purification and multi-Si wafer production stage data are from REC Solar and they are not representative of industry average. The wafer thicknesses analyzed are 180 µm for mono-Si and 200 µm for multi-Si technologies [4].

Take back and recycling stages have not been included in this report presented in the paper.

It is noted that greenhouse gas emission indicator, beside the other indicators, such as energy payback time, strongly

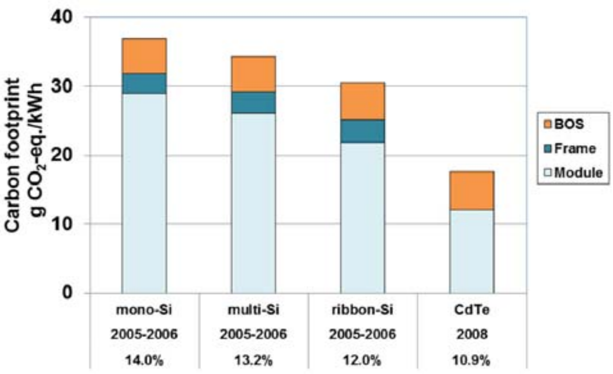

Figure 2. Greenhouse gas (GHG) emissions of rooftop mounted PV systems estimated from the currently available LCI data for European production and installation, and lifetime of 30 years [4]

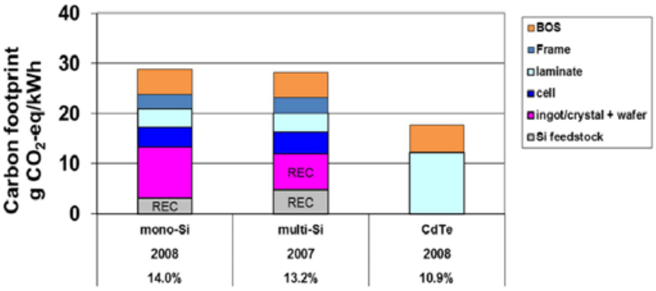

Figure 3. Greenhouse gas (GHG) emissions of rooftop mounted PV systems for European production and installation, and lifetime of 30 years; the corresponding LCI data are not publically available [4]

depend on the location of the photovoltaic system operation and the locations of the supply chain. For example, for operation in the US – South West (irradiation 2400 kWh/m$^2$/yr), the greenhouse gas emission per kWh would be lower, whereas for operation in central Europe (irradiation 1100 kWh/m$^2$/yr), it will be higher.

### *D. Single Electricity Sources and Electricity Mixes*

The study conducted in France refers to the influence of different electricity sources used for manufacturing the photovoltaic modules on the global impacts of the solar electricity (Fig. 4) [8]. Electricity produced by coal is average European production, and it brings the highest emission of CO$_2$ -eq/kWh of solar electricity. Nuclear power presents low CO$_2$ eq. emission, but the highest non-renewable primary energy use, which is important for the indicator of energy payback time, and it also has a negative impact on the environment. Use of renewable energies – hydro, wind and photovoltaic reduces the global warming impacts of solar electricity.

Results from Fig. 4 bring important information but are rarely representative of the energy used in photovoltaic industries. It is more realistic to use the electricity mix from the effective network for manufacturing photovoltaic systems. Fig. 5 shows CO$_2$ emission of different countries, which are the largest manufacturers of photovoltaic systems. Solar electricity is produced by photovoltaic installations fabricated with different electricity mixes. The transport values are calculated to bring the components of photovoltaic system from the country where they are manufactured to the French territory where they are installed.

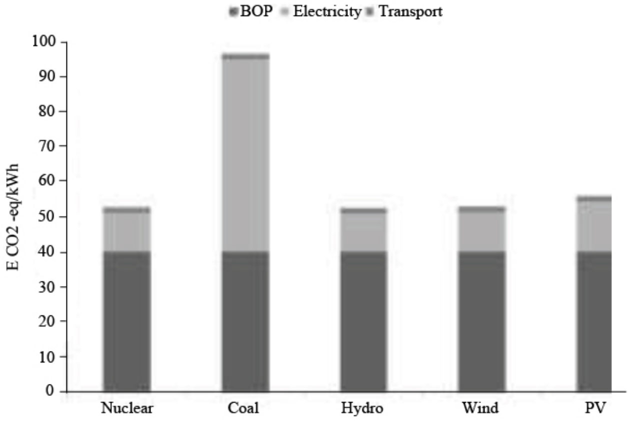

Figure 4. Carbon dioxide emission of solar electricity produced by PV installations fabricated with different source of electricity (where BOP is Balance of Processes) [8]

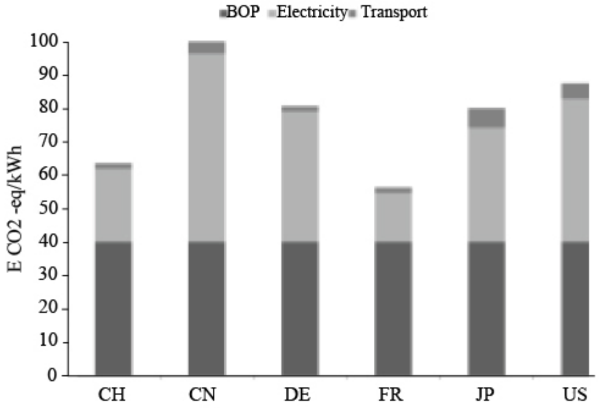

Figure 5. Carbon dioxide emission of solar electricity produced by PV installations fabricated with different electricity mixes (where BOP is Balance of Processes) [8]

Use of different electricity mix brings a large difference in the level of CO$_2$ emission of the solar electricity while energy payback time does not change as much if there is a variation in the used electricity mix [8].

## IV. FUTURE FORECAST

Based on the latest research results summarized in Table II it can be seen that the greenhouse gas emission of photovoltaic systems are well below those of fossil energies. If we take that the overall production of electricity generates an average of 0.6 kg CO$_2$ –eq/kWh [6], although this value varies from country to country, it is possible to calculate how many CO$_2$ –eq. will be saved throughout their lifespan.

The ecological footprint may be evaluated in terms of environmental gains resulting from the expected reduction in greenhouse gas caused by the use of photovoltaic systems. Once installed, the systems do not emit greenhouse gas, with the exception of the diesel generators and the transportation of maintenance services.

For the systems connected to the network, the emission of 12 – 25 g CO$_2$ –eq/kWh is taken into account and the results show that almost 4 billion tons of CO$_2$ –eq could be saved by 2050. This is the prediction of the European Photovoltaic Industry Association (EPIA) [6]. And for the autonomous systems, the anticipated savings is 6 tons of CO$_2$ –eq. For 15 and 50 Wp systems with a lifespan of more than 20 years, 8.9 tons of CO$_2$ –eq could be saved. The predictions go even further, considering that the implementation of photovoltaic plants in developing countries, combined with a generalization of systems connected to the network in order to supplement the hybrid systems and reduce emissions related to the transfer of technology from the supplier country to the consumer country would be even more beneficial in ecological terms with more than 26 tons of CO$_2$ –eq/kWh saved per site implemented [9].

TABLE II. GREENHOUSE GAS EMISSION RESULTING FROM DIFFERENT ENERGY SYSTEMS [6]

| Energy system | Average emission (g CO2 –eq/kWh) |
|---|---|
| PV Systems | 15 – 187 |
| Coal | 800 – 1280 |
| Oil | 519 – 1200 |
| Natural Gas | 360 – 991 |

## V. EXAMPLES OF SILICON PHOTOVOLTAIC SYSTEMS

Table III and Table IV show examples of the life cycle assessment (LCA) of mono-Si and multi-Si photovoltaic systems, respectively [10]. Two main indicators are presented, and they are energy payback time (EPBT) and greenhouse gas (GHG) emission. The photovoltaic systems range from small - scale to large - scale installations, all over the world.

If we take for an example multi-Si PV systems in Japan and in Greece, installed in 2005., it can be seen that the greenhouse gas emission is doubled in Greece, although the systems have the power of 3 kW each. The difference in results is a consequence of disparities in regional climatic conditions, as in other input data, specific for each location and for each photovoltaic system. This means that the impacts on the environment for specific location can be only predicted on the basis of the results for the location and installed system with similar features.

## VI. CONCLUSION

Greenhouse gas emission is an important indicator for the life-cycle analysis of photovoltaic systems. Based on this, the assessment of the system sustainability can be done as well as comparative analysis of suitability of the required system. However, for complete evaluation of the photovoltaic system all the predicted indicators have to be taken into account.

Use of country – specific electricity mix for manufacturing the components of the system is very significant input data, especially for the greenhouse gas emission. And for electricity production the most important is country potential for solar energy. Republic of Serbia has some of the best solar resource in Europe and solar irradiation is approximately 1400 kWh/m2/yr, which is around 40% higher than the European average [11].

Values of the life cycle assessment for a specific location cannot be obtained on the basis of the researches conducted abroad, but the results can be predicted.

This paper represents a review of up-to-date available data for greenhouse gas emission and a sort of promotion of sustainable electricity systems for our country, which is in correlation with legal directives of using renewable energies. Based on life-cycle analysis effectiveness of the photovoltaic system can be determined and also an impact on the environment.

TABLE III. LIFE CYCLE ASSESSMENT OF MONO – SI PHOTOVOLTAIC SYSTEMS [10]

| S. no. | Year | Location | Efficiency (%) | Power rating | Life time (years) | EPBT (years) | GHG emission (g-CO2/kWh) |
|---|---|---|---|---|---|---|---|
| 1. | 1990 | US | 8.5 | 300 kW | 30 | na | 280.0 |
| 2. | 1997 | Japan | na | 3 kW | 20 | 15.5 | 91.0 |
| 3. | 2000 | Netherlands | 14.0 | na | 30 | 3.2 | 60.0 |
| 4. | 2002 | India | 13.0 | 35 W | 20 | na | 64.8 |
| 5. | 2006 | UK | 11.5 | 14.4 kW | 30 | 8 | 44.0 |
| 6. | 2006 | Singapore | 7.3 – 8.9 | 2.7 kW | 25 | 5.87 | 217.0 |
| 7. | 2006 | Singapore | 10.6 | 2.7 kW | 25 | 4.47 | 165.0 |

TABLE IV. LIFE CYCLE ASSESSMENT OF MULTI – SI PHOTOVOLTAIC SYSTEMS [10]

| S. no. | Year | Location | Efficiency (%) | Power rating | Life time (years) | EPBT (years) | GHG emission (g-CO2/kWh) |
|---|---|---|---|---|---|---|---|
| 1. | 2003 | China | 12.8 | 100 MW | 30 | 1.7 | 12.0 |
| 2. | 2005 | Japan | 10.0 | 3 kW | 30 | na | 53.4 |
| 3. | 2005 | Italy | 10.7 | 1 kW | 20 | 3.3 | 26.4 |
| 4. | 2005 | Greece | na | 3 kW | 20 | 2.9 | 104.0 |
| 5. | 2007 | US | 12.92 | 33 kW | 20 | 5.7 | 72.4 |
| 6. | 2008 | China | 12.8 | 100 MW | 30 | 1.9 | 12.1 |
| 7. | 2008 | China | 15.8 | 100 MW | 30 | 1.5 | 9.4 |

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