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Eco-efficiency Analysis of Photovoltaic Modules

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1 Summary

This examination was conducted on behalf of the Bavarian State Ministry of the Environment and Consumer Protection. It analyzes a future-oriented picture of the impact of PV systems on the environment based on the status quo and considers the complete life cycle as well as the costs for operating PV systems. The manufacture of general PV systems (module and system components), their operation in various cases and their end of life treatment are assessed. Current production processes are portrayed for cell-based silicon technologies (monocrystalline and multicrystalline) as well as for thin-film technologies (CdTe[1] and CIS[2]). Based on that, the impact of further developments is examined, e.g., the use of various recycling methods, improvements in basic material manufacturing and the processing techniques. Unforeseen incidents such as fires or unauthorized disposal of defective or old modules are not a subject to review. The examination was supported by a technical advisory board, whose representatives belong to companies active in the photovoltaics value chain as well as to representatives of the ordering customer.

The ecological assessment covers the analysis of seven effects on the environment, which are combined to show their overall impact on the environment: the ecology index. Due to the very dynamic market development and the cost information only available from tendered prices, the electricity generation prices are approximated technology-independent using the feed-in tariffs in the German Renewable Energy Act (EEG). Accordingly, all technologies are classified equally based on the specified classification of the examined application cases pursuant to EEG (rooftop up to 30 kWp, rooftop starting from 100 kW and ground-mounted others).

Within the framework of the examination, the PV technologies are depicted based on production facilities for module manufacturing with very different production capacity and technological maturity. The respective overall impact on the environment is influenced decisively by economies of scale in production. There are only slight differences with respect to the impact on the environment for the examined silicon-based PV systems (monocrystalline and multicrystalline). This analysis is based on data concerning module manufacturing with high production capacities (larger than 500 MWp). The analysis of CdTe-based systems is based on data from a manufacturer with stable production (capacity >500 MWp), which already ensures high-quality recycling of its modules today and a mid-sized manufacturer, which is setting up a new production line (>50 MWp). The difference in the ecology index of approx. 23% between the two examined CdTe systems is due to the different state of technological development in laminate manufacturing. In addition, the differences are also a result of one of the manufacturers having already established high-quality PV module recycling. Within the context of the examination, the CIS-based PV systems are analyzed based on two different module/laminate types that are produced in facilities with comparably small capacities (>100 and <25 MWp). The environmental impact of both CIS systems is similar. However, the composition of the ecology index varies according to the materials used.

[1] Cadmium telluride (CdTe) is a crystalline compound of the metals cadmium and tellurium.

[2] CIS is an abbreviation for the group of compound semiconductors, which are composed of the elements copper, indium or gallium as well as sulfur or selenium. CIS = CIGS & CIGSe.

Eco-efficiency analysis of technologies based on the status quo

The energy payback times of the examined PV systems, which range from 0.55 to 1.3 years, take into account the total amount of energy used for manufacturing the systems and vary according to application types and technology. Accordingly, during their operating life all module types generate a multiple of the energy required in their production. The values apply to the selected installation site, Nuremberg, a central European site with good solar energy influx values. Better values would result from southern European sites.

The overall environmental impact of generating electricity from photovoltaics is 10 to 20 times smaller than the impact of fossil fuel electricity generation. However, it must be noted that "electricity from photovoltaics" and "electricity from non-renewable energy sources" differ in other aspects besides their environmental impact, e.g. the power variability of current photovoltaics. In this context, the **environmentally-related differences** between the **individual PV technologies** can be interpreted as small. However, the composition of the ecology index still varies due to the fundamentally different production processes of wafer-based and substrate-coated PV modules/laminates. Semiconductor and module manufacturing are decisive factors for the former, and the expenses in glass manufacturing are the focus for the latter.

When **comparing the different application types** of PV systems, the large industrial rooftop application has the best ecology index assessment with comparably low feed-in tariffs. Within this application, CdTe modules have the least environmental impact, closely followed by monocrystalline silicon modules or the examined CIS modules of smaller manufacturers. Ground-mounted systems represent the least expensive use for renewable electricity generation with photovoltaics (lowest EEG incentives). However, the overall environmental impact of ground-mounted systems is greater than that of large industrial rooftop applications. The environmentally-related difference between monocrystalline silicon and CdTe modules decreases with ground-mounted systems. The BOS expenses related to ground-mounted applications[3] is lower for silicon technologies. For small residential rooftops, as with large industrial rooftops, there are similarly higher feed-in tariffs and smaller differences in the overall environmental impact.

Environmentally-related adjustment options and potentials

From an environmental perspective, the **BOS** plays a significant role depending on the technology and the application type in particular. The fact that the module technologies became increasingly more efficient in the past has resulted in the environmentally-related contribution of the BOS becoming more significant in the overall result. Correspondingly, the use of existing infrastructure is evaluated as positive, e.g. attachment on existing slanted rooftops or the integration of PV systems into existing electronic systems (use of available transformer capacities).

The potential of **high-quality recycling** of PV modules is proving to be significant for the environment. In contrast to status quo recycling which is primarily aimed at the fulfillment of mass-related recycling quotas, optimal (high-value) recycling of silicon modules for example can result in twice as many environmental benefits. Overall, the environmental impact can be reduced by approx. 10% through the establishment of high-quality PV recycling.

[3] BOS "Balance of System": all system peripherals required for system operation

An **increase in efficiency** was found for all PV technologies from **2011 until 2012**. This is primarily due to the increase in efficiency, both in terms of module efficiency and economies of scale with the increased throughput rate of production lines. Savings of approx. 9 to 17% on the ecology index are achieved in this way.

With regards to **mid-term improvements,** targeted efficiency increases in production (along with optimization of thickness and quality of glass and reduction of plastic) will result in further improvements of the same magnitude as during 2011/2012. In terms of the forecasted development of efficiencies, an improvement potential of 23 to 33% is possible with the same amount of production expenses.

The **specific annual yield** per application type and PV technology has a decisive influence on the environmental impact assessment. In addition to the different PV technologies, this assessment is also determined by **distribution of production and specific features in the respective design** of the overall PV systems, e.g. the selection of the size and number of inverters or string distribution. The environmental impact would be probably reduced, especially for newer thin-film technologies of smaller manufacturers thanks to a more specific design of the total system related to PV technologies.