Presented at the WCPEC-8, 8th World Conference on Photovoltaic Energy Conversion, 26-30 September 2022, Milan, Italy

CO_2 EMISSIONS OF SILICON PHOTOVOLTAIC MODULES – IMPACT OF MODULE DESIGN AND PRODUCTION LOCATION

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ABSTRACT: CO_2 emissions of two different module designs (conventional glass-backsheet or novel frameless glass-glass modules) produced at three different locations (China, Germany or the European Union, EU) are determined and compared in a life cycle assessment (LCA), using current inventory data and differentiated electricity yields of the modules. The results show that lower environmental impacts are obtained for glass-glass compared to glass-backsheet modules and for a production in the EU and Germany compared to China. Glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to 810 (750), 580 (520) and 480 (420) kg CO_2-eq/kW$_p$, respectively. This corresponds to CO_2 emission reductions of 30% for Germany and 40% for the EU compared to Chinese production, and 8% to 12.5% reduction in glass-glass compared to glass-backsheet modules. The CO_2 emissions of the produced electricity, excluding balance of system (BoS), amount to 13-30 g CO_2-eq/kWh, depending on the production location and electricity yield of the modules which is based on warranty yield calculations with longer lifetimes for glass-glass than glass-backsheet modules. It is shown that module efficiency, energy requirements, silicon consumption and electricity mix used at the production location are significant levers for future reductions of environmental impacts. Furthermore, it is emphasized that up-to-date inventories and differentiated electricity yield calculations as well as current modelling of electricity mixes are important to incentivize the development of sustainable module designs.

Keywords: life cycle assessment, crystalline silicon, glass-backsheet module, glass-glass module

1 INTRODUCTION

Modules based on silicon solar cells are dominating the photovoltaic (PV) market and are considered as a green technology for the supply of renewable and emission-free energy. However, the production of the solar cells, the encapsulation and interconnection of them in the modules, as well as the transport and disposal or recycling, have a non-negligible impact on the environment and resource consumption. Therefore, an overall assessment of the modules is essential for the success of the envisaged energy transition with its expected growth towards a multi-terawatt scale in the next decades.

In general, the CO_2 emissions of PV systems are significantly lower than those of conventional energy generation using, for instance, coal, but there are considerable differences in modules due to the module design (classic glass-backsheet or novel frameless glass-glass modules) and, in particular due to the production location (China, Germany or the European Union, EU).

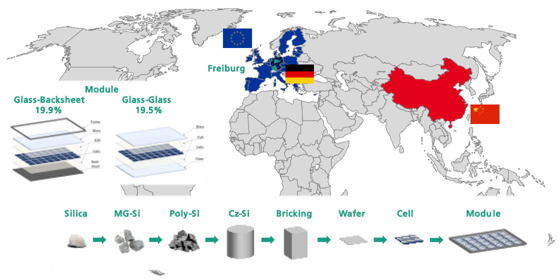

Figure 1: World map depicting the production location China (red), Germany (blue with green stripes) and the EU as of 2020 (blue) and the installation site in Freiburg, Germany, including the representation of the entire value chain (bottom) and the investigated glass-backsheet and glass-glass module designs with the corresponding efficiency (left).

In order to identify these differences, the CO_2 emissions of the PV modules were determined and compared in a life cycle assessment (LCA), using current inventory data and differentiated electricity yields of the modules.

In comparison to previous studies, more recent developments such as diamond wire saws for wafer production and current data in silicon, solar cell and module production of the years 2019/2020 were used as foreground data [1,2]. The existing literature also pays little attention to new developments in the module designs of PV systems and alternatives to the conventional glass-backsheet designs, such as frameless glass-glass designs with a higher expected market share [3], longer lifetimes [4,5] and reduced costs [6]. Furthermore, the recent shift in production to China is not always accounted for in PV LCAs and, therefore, the historic focus on inventory data from European producers prevails [7].

This study addresses the aforementioned aspects and reveals climate change impacts of the different module designs produced at different locations to identify benefits for the development of sustainable module designs.

It is shown that module efficiency, energy requirements, silicon consumption and electricity mix used at the production location are significant levers for future reductions of environmental impacts. Furthermore, it is emphasized that up-to-date inventories and differentiated electricity yield calculations as well as current modelling of electricity mixes are important to incentivize the development of sustainable module designs.

2 METHODOLOGY

The environmental impact of the modules was investigated over the entire life cycle from manufacturing to recycling in various categories, using the environmental footprint (EF 3.0) by the European Commission as the methodological approach, especially in terms of climate change, whereby the LCA performed is based on the guidelines of the International Energy Agency for PV systems (IEA PVPS) [8]. For the assessment of the impact on climate change, an indicator developed by the Intergovernmental Panel on Climate Change (IPCC) 2013 was used to determine the CO_2 equivalent emissions of the modules for a period of 100 years [9]. For this purpose, the material and energy consumptions to produce the modules along the entire value chain were implemented in SimaPro 9.0 [11] with background data from ecoinvent 3.7 [11] In ecoinvent 3.7 the electricity mix for China is from 2014 and for Germany and EU from 2017. An update of the current electricity mix of China, Germany and the EU is in preparation.

3 RESULTS AND DISCUSSION

The comparison of the entire value chain for a complete production of the PV modules in China, Germany and the EU shows clearly that a complete glass-backsheet module production in the EU or Germany causes about 41% and 28% less CO_2 emissions, respectively, compared to China (480 and 580 kg versus 810 kg CO_2-eq/kW$_p$), see Figure 2 (top).

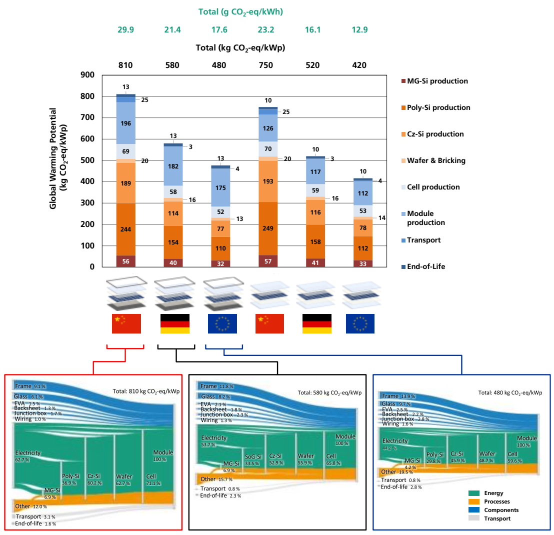

Figure 2: CO_2 emissions of glass-backsheet and glass-glass module designs for the different production processes (top) and share of energy, processes, components and transport for the production locations China, Germany and the EU (bottom). The total global warming potential (GWP) in shown as kg CO_2-eq/kW$_p$ (top, black) and g CO_2-eq/kWh (top, green).

The main reason for this difference can be found in the specific electricity mix at the production location. While in China the energy is predominantly generated from fossil fuels using coal and renewable energy represents only a small share of the electricity mix, the total energy provided from renewable sources in Germany and the EU is much higher. In addition, it is also shown that frameless glass-glass modules have even lower CO_2 emissions compared to glass-backsheet modules. For a glass-backsheet module produced in Germany, the shares of energy, processes, components, and transport were also broken down in more detail, see Figure 2 (bottom). It can be seen that the energy required for the production of the module is the main cause of the GWP with up to 62.7%, 53.7% and 44.2% for China, Germany and the EU, respectively.

The CO_2 emissions of the produced electricity, excluding BoS, amounts to 23.2-29.9 g CO_2-eq/kWh for China, 16.1-21.4 g CO_2-eq/kWh for Germany and 12.9-17.6 g CO_2-eq/kWh for the EU, assuming an electricity yield calculation based on different module performance warranties given by module producers with almost 30 years lifetime for glass-glass modules and 25 years for glass-backsheet modules and at a central Europan installation location (Freiburg, Germany, with 1391 kWh/(m^{2}a) solar irradiation).

The results underline that powerful and durable modules are indeed a promising pillar for a climate-neutral energy supply in the future. The production generates fewer CO_2 emissions than assumed in previous studies and migrating the complete production to the EU or Germany instead of China reduces CO_2 emissions, thus mitigating climate change. Therefore, a paradigm shift must take place in the future to ensure a sustainable and cost-effective development of the PV industry by re-evaluating the production locations, especially since the cost of CO_2 emissions will increase from the currently 25 €/t up to 55 €/t by 2025 [12] in Germany and even up to 75 €/t worldwide, which is discussed for 2030 [13].

5 CONCLUSION AND OUTLOOK

The results show that lower environmental impacts are obtained for glass-glass compared to glass-backsheet modules and for a production in the EU and Germany compared to China. Glass-backsheet (glass-glass) modules produced in China, Germany or the EU are linked to CO_2 emissions of 810 (750), 580 (520) and 480 (420) kg CO_2-eq/kW$_p$, respectively. This corresponds to CO_2 emission reductions of 30% for Germany and 40% for the EU compared to Chinese production, and 8% to 12.5% reduction in glass-glass compared to glass-backsheet modules. The CO_2 emissions of the produced electricity, excluding balance of system (BoS), amounts to 13-30 g CO_2-eq/kWh, depending on the production location and electricity yield of the modules which is based on warranty yield calculations with longer lifetimes for glass-glass than glass-backsheet modules.

It is shown that module efficiency, energy requirements, silicon consumption and electricity mix used at the production location are significant levers for future reductions of environmental impacts. Furthermore, it is emphasized that up-to-date inventories and differentiated electricity yield calculations as well as current modelling of electricity mixes are important to incentivize the development of sustainable module designs.

ACKNOWLEDGEMENTS

The authors acknowledge the funding of the work by the German Ministry of Economic Affairs and Climate Action under Grant No. 03EE1095B "KoMoGER".

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