Carbon Footprint Analysis of Floating PV systems

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Executive Summary

Floating PV is a relatively new but rapidly growing segment of the photovoltaics (PV) market. So far, no detailed public life cycle inventory (LCI) data about operational floating PV (FPV) systems is available in literature. Therefore, the Dutch research organisation TNO has gathered and analysed LCI data for two operational systems and publishes the results in this first IEA PVPS Task 12 publication on floating PV. This study only focuses on one single environmental impact factor, the carbon footprint. The goal of the study is to collect LCI data for two different floating PV systems on small inland water bodies in Western Europe with very low wave height, in order to quantify the carbon footprint of these systems. The lifetime, performance ratio and degradation rate of the PV modules in the floating PV systems are assumed to be identical as in ground-mounted PV systems, since empirical data for these parameters is not available.

The functional unit for this analysis is defined as the generation of 1 kWh of AC electricity delivered to the grid. The system boundary is at the high voltage side of the transformer. Floating PV systems data was collected by sending questionnaires to the owners of two different systems. Both systems are located on small inland water bodies in Western Europe and are operational since 2021. However, they have different floater compositions. System FPV_A (located in Germany) has floaters made predominantly from HDPE (High-density polyethylene). System FPV_B (located in the Netherlands) has steel/HDPE floaters. For each of the two systems, LCI data for the floating support structure have been received from the manufacturers, compiled, verified and published. For the electrical system, LCI data were collected from one of the systems (system FPV_B). Two ground-mounted systems were defined as (hypothetical) reference systems. For these systems no primary data was collected. Instead, background data from UVEK DQRV2:2022 was used to describe these systems. Except for the support structure and electricity yields both FPV and both GPV systems are identical.

Finally, the yield prediction tool BIGEYE was used to model the lifetime energy yield of both systems for the reference location Cologne (Germany), with Global horizontal irradiation (GHI) of 1062 kWh/(m^2 yr). In a similar way the energy yield was modelled for a ground-mounted system with east-west orientation (GPV_ew) and for a ground-mounted system with optimum orientation and tilt (GPV_op). The details of this system are shown in Table S1. Both FPV and GPV systems use the same values for the following parameters: 20.5% PERC PV modules, made in China, degradation rate 0.7%/year, performance ratio (PR) 0.80, bifaciality factor 0, albedo 0, lifetime 30 year, inverter lifetime 15 year. Due to the novelty of floating PV, there is no systematically collected field data available for parameters such

as lifetime, degradation rate and performance ratio of floating PV systems. Instead, for these parameters the default values were used that are normally used for ground-mounted systems.

Table S1: Characteristics of the floating PV systems FPV_A and FPV_B that are assessed in this report. GPV_ew and GPV_op are ground-mounted reference systems (source: UVEK DQRV2:2022).

Component	Unit	FPV_A	FPV_B	GPV_ew	GPV_op
Main material of support structure	-	HDPE	Steel, HDPE	Steel, aluminium	**Steel, aluminium**
Orientation	°	180	90+270	90+270	**180**
Tilt angle	°	11	12	12	**38**
Ground coverage ratio (GCR)	%	60	87	87	**60**
Power density	[kWp/ha]	1.23	1.78	1.78	**1.23**
Location	-	Cologne (DE)	Cologne (DE)	Cologne (DE)	Cologne (DE)
Specific energy yield	kWhac/ (kWp yr)	889	795	962	**962**
Rated power	**kWp**	**1'479**	**29'770**	**n.a.**	**n.a.**

The result was a modelled average specific energy yield per year of 889 kWhac/(kWp yr) for FPV_A; 795 kWhac/(kWp yr) for FPV_B; 962 kWhac/(kWp yr) for GPV_op; and 795 kWhac/(kWp yr) for GPV_ew. These differences in estimated yield are caused exclusively by the different orientations and tilt angles of the systems. While system FPV_A is south-facing, system FPV_B is east/west-facing. Both floating systems have a non-optimal tilt angle of 11° and 12°, respectively. Ground-mounted system GPV_ew faces east/west with a tilt angle of 12°, as is becoming more and more customary for ground-mounted systems. For the ground-mounted system GPV_op the optimum tilt angle of 38° and an optimum south-facing orientation is assumed. Note that this tilt is optimized for Western European locations (latitude 50° N). At locations closer to the equator the optimum tilt angle is lower and the energy yield of the other three systems will be higher.

Based on these LCI data and background data from UVEK DQRV2:2022, the carbon footprint was estimated for each of the two floating PV systems and for the ground-mounted reference systems, both on a per kWp basis and on a per kWh basis. The outcomes on a per kWp basis (AC) were as follows: FPV_A: 1280 kgCO_2eq/kWp; FPV_B 1300 kgCO_2eq/kWp; and both GPV systems had the same per kWp result: 1100 kgCO_2eq/kWp. The carbon footprint per kWp for both GPV systems is identical, since the only differences between these systems are their orientation, tilt and ground coverage ratio.

The outcomes on a per kWh basis (AC) were as follows: FPV_A: 49 gCO_2eq/kWh; FPV_B 55 gCO_2eq/kWhac. The carbon footprint for the reference ground-mounted PV systems were modelled as: GPV_ew: 46 gCO_2eq/kWhac; GPV_op: 38 gCO_2eq/kWhac. This means that the carbon footprint of the floating PV systems is about 15% higher than that of a ground-mounted PV system with east-west orientation and about 25% higher than that of a ground-mounted system with with south orientation and optimum tilt. The largest contribution to these carbon footprints is from the manufacturing of the PV module (60% to 70%, depending on the system). For comparison, the carbon footprint per kWh of the average electricity mix in Germany and the Netherlands in 2018 is around 380 gCO_2eq/kWh, according to UVEK 2022 [2]. This means that for this location the carbon footprint of both FPV power plants is 7 times lower than the grid mix.

In a sensitivity analysis, the influence of the lifetime of various components of the floating PV systems on the carbon footprint of the system has been tested. As can be expected, a shorter lifetime of the system leads to a higher carbon footprint per kWh. Reduction of the overall system lifetime from 30 to 20 years leads to 50% increase of the carbon footprint per kWh. The component with the biggest impact on the carbon footprint per kWh is the PV module. Reducing the module lifetime to 20 years leads to an increase of the carbon footprint per kWh by 28% for system FPV_A and by 31% for system FPV_B. The impact of the lifetime of the support structures is much smaller. A reduction of the lifetime of the support structure to 20 years leads to an increase of the carbon footprint per kWh by 19% for system FPV_A and by 16% for system FPV_B. The lifetime of other components such as the inverter and the DC cables have even less impact on the carbon footprint per kWh of the FPV system. This suggests, perhaps not expectedly, that from a carbon footprint perspective it could be worthwhile to replace components such as the inverter and DC cables if this leads to a substantial increase in the energy yield.

The authors have noted the following implications of our results relevant to owners and designers of floating PV systems:

- The outcome of this analysis suggests that, if the projected energy yield is met, floating PV systems on small inland waters, like ground-mounted PV systems, can significantly reduce the carbon emissions for electricity generation, being 7 times lower than that of the average grid mix both in Germany and the Netherlands in 2018.
- It is essential for the carbon footprint (and for the business case) that the expectations on lifetime energy yield are met, as well as the projected lifetime of the system and its components. Therefore, it is recommended to closely monitor the degradation rate of the PV modules, as well as the performance and reliability of the overall system and the need for maintenance.
- We analyzed three major options to further reduce the carbon footprint of the floating PV systems (in order of largest impact): manufacturing PV modules with lower carbon electricity sources. Here we compared manufacturing in the EU instead of China (country-average); using recycled raw (secondary) materials for the support structure; recycling the HDPE at end of life instead of incinerating it.[1] When these are all implemented the carbon footprint of the floating PV systems can be further reduced by over 40%.

This report is the first publication of IEA PVPS Task 12 on floating PV. The authors have the following suggestions for further research:

- Lifetime, performance ratio and degradation rate of the PV modules in FPV systems are the main unknowns that will determine the system performance. Key degradation patterns of PV modules in FPV systems should be identified as well as the long-term benefits, if any, of dedicated PV modules for FPV systems (e.g., lower degradation rate).
- For a full environmental assessment of floating PV, all environmental impacts should be taken into account, not just the carbon footprint that was addressed in this report. Future research is needed to assess all other environmental impacts, including location-independent impacts such as mineral resource use, but also location-dependent impacts such as freshwater or marine ecotoxicity and impact on ecosystems.
- It is strongly recommended that operational data of floating PV are systematically collected, for various environments and various types of systems. The sensitivity analysis has shown that the carbon footprint of floating PV systems is highly dependent on the lifetime energy yield of the PV system, as well as the lifetime of the PV system. Long term monitoring data on these quantities is

[1] Both system owners indicate that they plan to recycle the HDPE at end of life. This was not used as default end-of-life scenario because the LCA guidelines require that the default scenario is based on current common practice for that material.

currently lacking because floating PV is a relatively new application. This is also essential to corroborate the business case for floating PV.

- It is also recommended to broaden the analysis by including other floating systems. Special attention should be paid to floating PV systems that track the sun. If they don't have a shorter lifetime or need more maintenance, they can have a higher lifetime energy yield and thus could potentially have a lower carbon footprint per kWh.
- This study was focused on floating PV system on inland waters with low wave height in Western Europe. The outcome is not necessarily valid for floating PV in other environments, especially locations with higher wave heights and heavier wind conditions such as offshore floating PV. For other environments, separate studies should be done taking into account all relevant differences, including system design, material use, lifetime energy yield and lifetime.

If the degradation of the PV modules is limited, the carbon footprint of the floating PV systems that were analyzed is 7 times lower than the average electricity grid mix both in the Netherlands and Germany in 2018, and 3-4 times lower than the EU grid mix target for 2030. This means that, from a greenhouse gas emissions point of view, they can complement ground-mounted PV systems.