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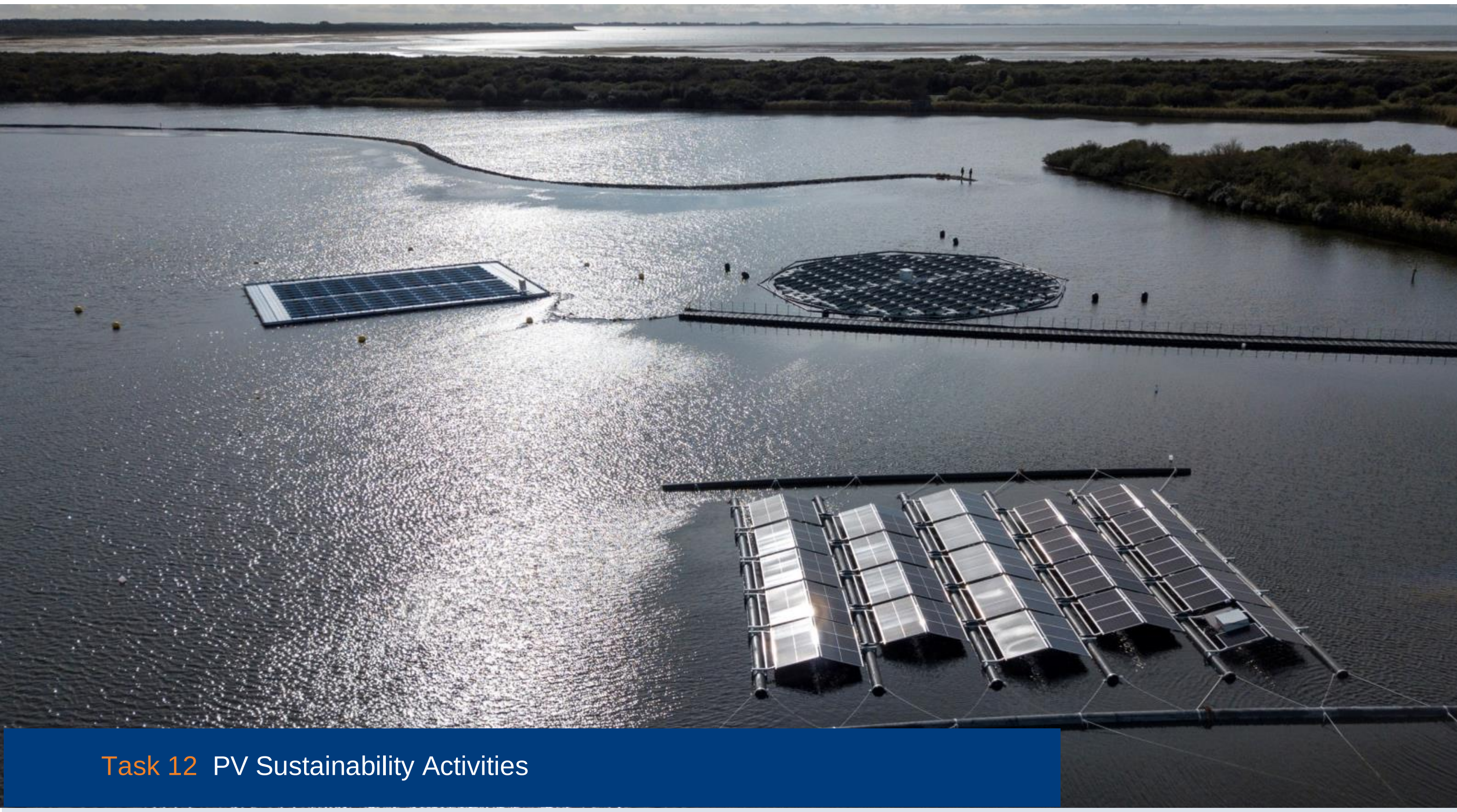

Task 12 PV Sustainability Activities

PVPS

Carbon Footprint Analysis of Floating PV systems
2024

Report IEA-PVPS T12-29:2024

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The 25 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance, the Solar Energy Industries Association, the Solar Energy Research Institute of Singapore and Enercity SA are also members.

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What is IEA PVPS Task 12?

Task 12 aims at fostering international collaboration in safety and sustainability that is crucial for assuring PV grows to levels making it a major contribution to the needs of the member countries and the world. The overall objectives of Task 12 are to 1. quantify the environmental profile of PV in comparison to other energy technologies, 2. investigate circularity options for PV systems as deployment increases and older systems are decommissioned, and 3. define and address environmental health and safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy, material, and emission flows in all the stages of the PV life cycle. The second objective is addressed through analysis of strategies including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and TotalEnergies. Support from the U.S. Department of Energy and TotalEnergies are gratefully acknowledged.

Further information on the activities and results of the task can be found at: https://iea-pvps.org/research-tasks/pvsustainability/.

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COVER PICTURE

Floating solar installations at the Field lab on Lake Oostvoorne, the Netherlands (Photo credit: TNO)

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INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Carbon Footprint Analysis of Floating PV systems

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LIST OF ABBREVIATIONS

AC	Alternating current
CFP	Carbon footprint
cSi	Crystalline silicon
DE	Germany
DC	Direct current
EoL	End of life
FPV	Floating photovoltaic
FPV_A	Floating photovoltaic system A (HDPE/steel)
FPV_B	Floating photovoltaic system B (predominantly steel)
GHG	Greenhouse gas
GHI	Global horizontal irradiation
GPV	Ground-mounted photovoltaic
GPV_ew	Ground-mounted photovoltaic system with east-west orientation
GPV_op	Ground-mounted photovoltaic system with optimum orientation and tilt
HDPE	High-density polyethylene
IEA	International Energy Agency
kWh	Kilowatt-hour
kWp	Kilowatt-peak
LCA	Life cycle assessment
LCI	Life cycle inventory
MWp	Megawatt-peak
n.a.	Not available
NL	The Netherlands
PERC	Passivated emitter rear contact
PR	Performance Ratio
PV	Photovoltaic
PVPS	Photovoltaic power systems
TNO	Dutch research organisation TNO

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 tocollect 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 PV systems.
FPV_A and FPV_B are the floating PV systems 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 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).

[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.

- 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 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.

1 INTRODUCTION AND OBJECTIVE

Floating PV is a relatively new but rapidly growing segment of the PV market [1]. The main advantage of floating PV compared to ground-mounted PV is that no competitive use of land is needed. Limiting negative environmental impacts of floating PV systems is essential to make it a viable alternative. So far, no detailed public LCI data about operational floating PV systems is available in literature. Therefore, the Dutch research organization TNO has gathered and analyzed LCI data for two operational systems and publishes the results in this first IEA PVPS Task 12 publication on floating PV. The scope of this report is limited to the carbon footprint (CFP).

The objective of the report is to quantify the carbon footprint of two different floating PV systems on small inland water bodies with very low wave height.

Floating PV systems on the market are very diverse in design. Also, reliable public data on market shares of various system types is not available, since the market for floating PV systems is young and rapidly growing. For these reasons it is impossible to calculate a market average for floating PV systems. Instead, the carbon footprint of two operational systems with different designs (both from Western Europe and operational since 2021) has been determined and are shown separately.

2 SCOPE

2.1 Goal

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.

2.2 Functional Unit

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 transformers. The LCA includes all components of the AC-coupled PV systems up to and including the transformers (see Figure 1).

The following stages (according to EN 15804, 2013) are included:

- Product stage (Modules A1 to A3)
- Construction stage (Modules A4 and A5)
- Use stage (Module B): in this stage cleaning of panels and unscheduled repair and replacements are excluded because of lack of data.
- End of life stage (Module C): for each material the currently common end-of-life treatment is used as default scenario. Other end-of-life scenarios have been used in the sensitivity analysis.

Calculation is done according to the cut-off allocation method. For materials that are profitable to recycle (steel, aluminium) only the emissions for deconstruction, dismantling and transport to the recycling installation are allocated to the waste treatment process. For these materials the emissions of the recycling process are allocated to the secondary material. However, for materials that are *not* profitable to recycle (HDPE) the emissions of the recycling process are allocated to the waste treatment process.
Manufacturing equipment and infrastructure are excluded from the calculations.

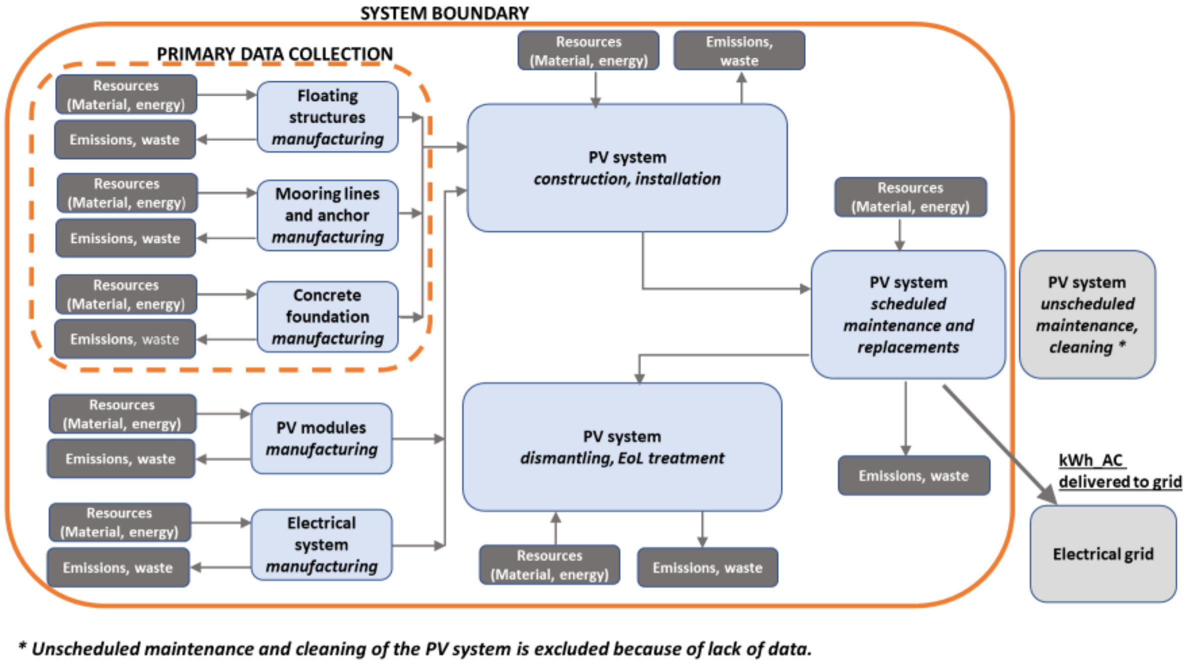

Figure 1: Flow diagram with system boundary.

2.3 System Design

Data has been gathered for two operational PV systems from different suppliers, with different orientations and different floater compositions: a) predominantly HDPE; b) steel/HDPE. System a) is south-facing but can also be installed as east/west-facing system. System b) is exclusively east/west-facing by design. Both systems are located on small inland water bodies in Western Europe (Germany and the Netherlands, respectively) and are operational since 2021. Figure 2 below shows both types of systems, seen from the air.

Figure 2: Aerial pictures of both floating PV systems (left: FPV_A, right: FPV_B).

System FPV_A with HDPE floaters is a 1.48 MWp system located in Germany, facing south. System FPV_B, with steel/HDPE floaters, is a 29.8 MWp system located in the Netherlands, facing east-west. The main characteristics of these systems can be found in Table 1 below. Figure 3 below shows sketches of both systems.

Two ground-mounted systems were defined as reference: GPV_ew with east-west orientation and 12° tilt; and GPV_op with south orientation and optimum 38° tilt. Apart from their orientation, tilt and ground coverage ratio (GCR) they are identical. The ground coverage ratio (GCR) of the systems GPV_ew and GPV_op has been chosen identical to respectively FPV_B and FPV_A.

**Table 1: Characteristics of the PV systems.[2]
FPV_A and FPV_B are the floating PV systems assessed in this report. GPV_ew and GPV_op are ground-mounted reference systems (source: UVEK DQRV2:2022).[3]**

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)
Rated power	kWp	1’479	29’770	n.a.	n.a.

[2] Source: personal communication (FPV_A , FPV_B); defined by the authors (GPV_ew, GPV_op).

[3] GPV_ew has east-west orientation and low tilt, GPV_op has optimum orientation and tilt. Both ground-mounted systems are identical except for orientation, tilt and ground coverage ratio.

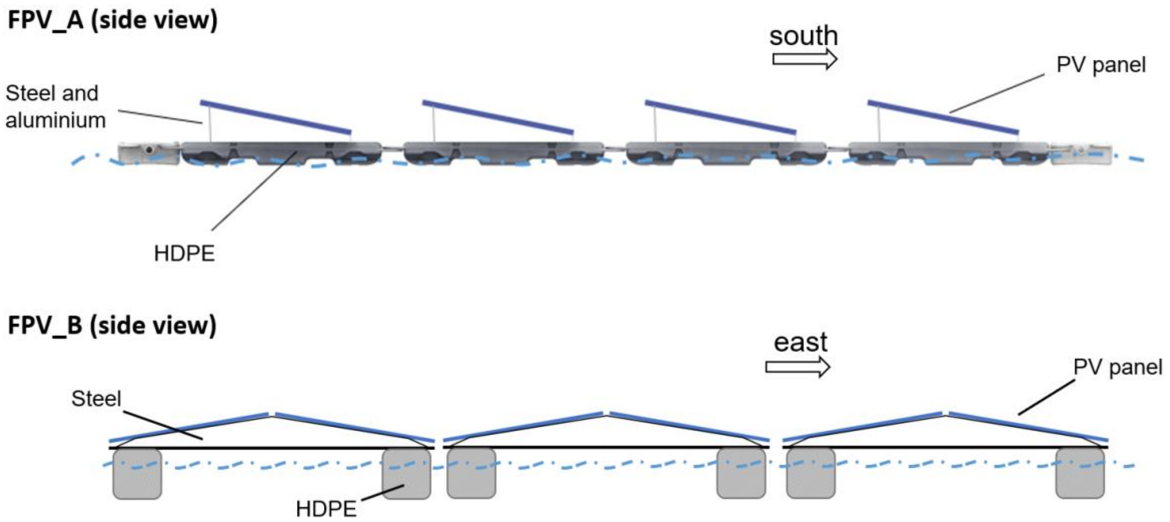

Figure 3: Sketches of the floating PV systems.

2.4 Allocation

The assessed systems do not include any multi-output processes (processes that generate various products) in the foreground. Therefore, no allocation is applied. All processes are modelled using the cut-off approach. For all inputs (such as steel) data is used from UVEK DQRV2:2022 which follow the recycled content approach.

2.5 Data Sources

For assessing manufacturing and installation of the floating PV systems foreground data was gathered from the system owners through a dedicated questionnaire. The data was checked for internal consistency and for consistency with datasheets from suppliers (collected from internet). Background data was taken from UVEK DQRV2:2022 [2], using SimaPro 9.3. Where applicable the methodology guidelines from IEA PVPS Task 12 were followed [3].

The gathering of foreground data focused on data for the floating substructures of the floating PV systems. For the electrical system (cables, inverters, transformer, etc.) data was gathered from one floating PV system (FPV_B) and used for both systems. Also, for the PV module data was gathered from floating PV system FPV_B and used for both systems as well as for the ground-mounted reference systems. The carbon footprint of this module was based on the carbon footprint for a glass-glass PERC module manufactured in China, as calculated by Mueller [8]. No foreground data was gathered for the ground-mounted systems. Instead, all data (including data for the support structure) were taken from UVEK DQRV2:2022.

Lifetime energy yield was modelled using system geometries and average climate conditions from the reference location Cologne, Germany according to MeteoNorm [4]. The calculations were performed using TNO’s BigEYE simulation software [5].

2.6 Impact Assessment Indicator

The environmental impact of the floating PV systems is quantified using the greenhouse gas emissions according to the IPCC 2013 GWP100 method in SimaPro 9.3. Other relevant environmental impacts were not included in this study. For a full environmental assessment of floating PV these should also be taken into account. This includes location-independent impacts such as mineral resource use, but also location-dependent impacts such as freshwater or marine ecotoxicity and impact on ecology. There is an increasing number of publications on these topics, including [10], [11]. Nevertheless, longitudinal studies of floating PV systems in various types of ecosystems are missing, as well as a comprehensive literature review.

3 LIFE CYCLE INVENTORY ANALYSIS

This chapter shows the results of the life cycle inventory analysis. It describes successively the support structures, the PV modules and systems, end-of-life emissions, and the lifetime energy yield.

3.1 Support structures

In this section the composition of the support structure and its life cycle inventory (LCI) are shown. The support structure includes all floating devices, anchors and all mooring and mounting materials such as cables, screws and pins. Electrical cables are not included since they are part of the electrical system.

3.1.1 Floating PV system A (HDPE floats)

Data on the composition of the support structure of floating PV system FPV_A was gathered from the system owner using a questionnaire. The results can be found in Table 2 below. Table A1 in Appendix A shows the LCI data in Ecospold format. Table 3 shows the carbon footprint of manufacturing for materials used for the support systems.

Table 2: Composition of the support structure of floating PV system FPV_A (HDPE) (Source: personal communication)

Component	number	Steel	Aluminium	HDPE	Concrete
Unit	[n/kWp]	[kg/kWp]	[kg/kWp]	[kg/kWp]	[kg/kWp]
Portative floats for PV panel	2.9	0	0	34	0
Long maintenance floats	0.79	0	0	5.1	0
Short maintenance floats	0.80	0	0	3.0	0
Connection screws	7.4	0	0	1.0	0
Cutter pins	7.4	0.074	0	0	0
Float caps	4.5	0	0	0.22	0
Panel fixing system	2.5	0.17	1.9	0	0
Concrete blocks[4]	0.043	0	0	0	170
Connection plates for anchoring	0.043	0	0.25	0	0
Shackles	0.17	0.11	0	0	0
Polyester ropes	0.043	0.016	0	0	0
Steel cables	0.043	0.28	0	0	0
Chains		0.79	0	0	0
Total		1.4	2.2	44	170

Table 3: Carbon footprint of support structure materials (cradle to gate) used in the systems FPV_A, FPV_B and GPV. (Source: UVEK DQRV2:2022)

Material	Origin	CFP [kgCO_2eq/kg]	FPV_A	FPV_B	GPV
HDPE	RoW[5]	4.3	X		
HDPE	RER	2.9	X	X	X
HDPE (recycled)	RER	1.6	X	X	X
concrete	GLO	0.14	X		X
galvanized steel	RER	2.9	X	X	X
Al wrought alloy	**GLO**	20	X		X

[4] The concrete in system FPV_A is used for the anchoring system. This does not depend on the FPV type but rather on the site. Without concrete the carbon footprint of system FPV_A is 3% lower.

[5] Based on processes “Polyethylene, HDPE, granulate, at plant {RER}” and “Blow moulding {RoW}”.

3.1.2 Floating PV system FPV_B (Steel/HDPE floats)

Data on the composition of the support structure of floating PV system FPV_B was gathered from the system owner using a questionnaire. The results can be found in Table 4 below. Table A2 in Appendix A shows the LCI data in Ecospold format.

Table 4: Composition of the support structure of floating PV system FPV_B (Steel/HDPE).
(Source: personal communication)

	Nr [1/kWp]	Steel [kg/kWp]	HDPE [kg/kWp]
Solar Boats	0.12	44	14
Inverter boats	0.0046	1.6	0.30
Anchors	0.0025	1.4	0.0
Total		47	15

3.1.3 Ground-mounted PV system (GPV)

As reference the ground-mounted PV system from UVEK DQRV2:2022 is used ("open ground construction, on ground/m2/RER"). The details of this system are shown in Table A3 in Appendix A.

3.2 PV modules and Electrical System

Both floating PV systems use 20.5% efficiency mono-Si PV modules. Also, the electrical systems for both systems are very similar. The greenhouse gas emissions of the PV modules and of the electrical system for all three PV systems are based on data from one floating PV system (FPV_B). This is done to simplify the comparison and because of the availability of detailed data. Such an approximation is deemed acceptable since the analysis focuses on the influence of the floating support systems on the carbon footprint of the floating PV systems and there are no inherent differences between the three PV systems in the PV module or electrical system[6].

[6] If we assume that all systems use string inverters, the major difference in electrical system design of the three systems might be the length of the DC cables which depends on the geometry of the system. However, the impact on the carbon footprint of the length of the DC cables is negligible, as can be seen from the sensitivity analysis in Figure 8. Doubling the length of the DC cables has the same effect as halving the lifetime of the DC cables.

3.2.1 PV modules

Floating PV system FPV_A and FPV_B both contain 20.5% PERC glass-glass PV modules with frame, manufactured in China[7]. The carbon footprint for this module (780 kgCO_2eq/kWp) is determined using data from Mueller [8] for a glass-glass PERC module manufactured in China. The value of Mueller is multiplied by a factor (19.4/20.5) to account for the higher module efficiency of 20.5%. After that the carbon footprint of the frame is added, using Mueller's data for a framed glass-back sheet module manufactured in China, again taking into account a correction factor for the module efficiency. To simplify comparison between both floating PV systems and the ground-mounted system, this module was also used for the PV modules in both GPV systems.

In the sensitivity analysis in section 5.2 the impact of using a module manufactured in Europe instead of China is evaluated. The carbon footprint of this 20.5% PERC glass-glass PV modules with frame is 460 kgCO_2eq/kWp. This is calculated in a similar way based on data from Mueller [8] for PERC glass-glass modules manufactured in Europe.

3.2.2 Electrical System

The electrical system includes the transformers and all electrical cables and equipment at its secondary side: transformers, inverters, AC and DC cables. The components of the electrical system of PV system FPV_B are shown in Table A4 in Appendix A. For the inverter a lifetime of 15 year is assumed and for the other components a lifetime of 30 year. As mentioned above, the electrical system of system FPV_A is assumed the same as for FPV_B, as well as for the reference ground-mounted PV system.

3.3 End of life

At the end of life of a PV system or its components the materials need to be removed and processed. Various options are available with different impacts on the environment ranging from landfill (if allowed), waste incineration, to recycling and in some cases re-use. The process descriptions for the end-of-life treatments of the materials used in the floating support systems can be found in Table A5 in Appendix A. The carbon footprint of these end-of-life treatments can be found in Table 5.

By default, end-of-life treatment of the systems were modelled based on current practice. For galvanized steel and aluminium this means recycling. Concrete is used as filling material for constructions or roads ('recycling'). For HDPE current practice is to incinerate it in a waste incineration installation. The owners of both floating PV systems indicate that their systems (including HDPE) will be fully recycled at end of life. Therefore, collection and recycling of

[7] As per the system owner, FPV_B contains modules JA Solar of type JAM72D30-535 MB [6]. Type and manufacturer of the modules used in FPV_A are unknown.

HDPE was also modelled[8]. Data for recycling of the support structures of ground-mounted systems is based upon [9][9].

Table 5: Carbon footprint of EoL treatments for various materials. (Source: UVEK DQRV2:2022)

Material	EOL treatment	CFP [kgCO_2eq/kg]	FPV_A	FPV_B	GPV
Concrete	Recycling	0.069	X		
HDPE	Incineration	3.1	X	X	
HDPE	Recycling[10]	0.54	X	X	
Galv. steel	Recycling	0.071	X	X	X
Aluminium	Recycling	0.071	X		

3.4 Lifetime energy yield

The lifetime energy yield of both types of systems has been modelled for a standard situation, using the yield prediction tool BIGEYE [5]. Table 6 shows the modelled lifetime energy yield (AC), at the high voltage side of the transformer(s). It includes system losses and degradation over lifetime and is valid for the conditions mentioned in this table. For better comparison, for several parameters standard conditions are used. These are assumed identical for the floating PV systems as for the ground-mounted PV systems.

Please note that the modelled energy yield of both floating PV systems is about 20% lower than the actual energy yield in year 1. This difference can be explained by the effect of the average degradation over lifetime (included in the model calculation through the PR) and by the variation of the yearly irradiation. Each factor can account for half of the difference.

[8] This process was modeled using the process “polyethylene production, high density, granulate, recycled RoW” from EcoInvent 3.8. The waste polyethylene was subtracted from the inputs for this process. Collection and transportation to the recycling installation was added. The process is used in the sensitivity analysis in section 5.4.

[9] Data from this publication were scaled in proportion to the carbon footprint per kWh for the PV module.

[10] The carbon footprint of recycling of HDPE is calculated from EcoInvent 3.8 data.

Table 6: Modelled energy yield for the four PV systems, with calculation parameters. (Location: Cologne (Germany), GHI: 1062 kWh/(m^{2}yr), module efficiency: 20.5%, PR: 0.80, lifetime: 30 year, albedo: 0, bifacial gain: 0.)

Parameter	Unit	FPV_A	FPV_B	GPV_ew	GPV_op
Lifetime energy yield (AC, HV)	[MWh/kWp]	26.7	23.8	23.8	28.9
Specific energy yield (AC, HV)	[kWh/ (kWp yr)]	889	795	795	962
Orientation	[°]	180	90+270	90+270	180
Tilt	[°]	11	12	12	38
Ground coverage ratio (GCR)	[%]	60	87	87	60
Power density	[kWp/ha]	1.23	1.78	1.78	1.23

In the two top rows of Table 6 one can see the outcome of the energy yield calculations: the modelled *lifetime energy yield* [kWh/kWp] and the modelled *specific energy yield* over lifetime in [kWh/(kWp yr)]. Under the assumptions used the modelled energy yield of system FPV_B is 11% lower than of that of system FPV_A. This is caused by its different orientation (east-west instead of south), whereas other parameters such as lifetime and degradation rate were assumed identical. The ground-mounted system GPV_op has the highest modelled energy yield. This is caused by its assumed optimal orientation and tilt, see further explanation below.

The values and origin of each of the parameters in Table 6 are specified here:

- *Location*: to simplify comparison of the outcomes, one common reference location is used for the four systems: Cologne, Germany (50.936 °N; 6.957 °E).

- *Global horizontal irradiation (GHI)*: Irradiance data for the reference location Cologne was taken from MeteoNorm [4], giving a yearly global horizontal irradiation of 1062 kWh/(m^2 yr).

- *Module efficiency*: The systems have identical mono-crystalline PV modules with a module efficiency of 20.5%. This value corresponds to the actual module efficiencies for systems FPV_A and FPV_B as supplied by the system owners.

- *PR*: A Performance Ratio (PR) of 80% is assumed for all four systems, in line with the recommendations of [3] for ground-mounted utility installations. The performance ratio (PR) describes the difference between the modules' (DC) rated performance (the product of irradiation and module efficiency) and the actual (AC) electricity generation (IEC 61724). It is here assumed to include age-related degradation (0.7%/year) over the lifetime of the system.

- *Lifetime*: A lifetime of 30 years is assumed for both floating PV systems and for the ground-mounted reference systems, in line with the recommendations of [3] for ground-mounted and rooftop-mounted systems.

- *Albedo* and *bifacial gain*: For albedo and bifacial gain a value of 0 is used for all systems, in line with the low reflectance of water surfaces, ground surfaces and support structures.

- *Orientation*: The orientation of floating system FPV_A and of ground-mounted system GPV_op is set at the optimum value (180°, facing south), in line with the recommendations from [3]. Floating system FPV_B and ground-mounted system GPV_ew are east-west systems and have an orientation of 90°+270°. For systems FPV_A and FPV_B these values correspond to the actual orientation, as supplied by the system owners.

- *Tilt*: The two floating systems FPV_A and FPV_B are designed for low tilt. For these systems the actual tilt is used, as specified by the system owners (respectively 11° and 12°). The tilt of the ground-mounted system GPV_op is set at the optimum value (38°), in line with the recommendations from [3]. Ground-mounted system GPV_ew has a low tilt of 12°, like the east-west systems it represents.

- *Ground coverage ratio (GCR)*: The ground coverage ratio for the two floating systems is calculated using the data supplied by the system owners. The ground-mounted system GPV_ew is assumed to have the same ground coverage ratio as floating system FPV_B, whereas GPV_op has the same ground coverage ratio as floating system FPV_A.

- *Power density:* The power density for the PV systems is calculated using the module efficiency and the ground coverage ratio. Note that this is an idealized power density, that only takes into account the area needed for the PV modules and the spacing between the modules. Any other area of the PV farm is neglected, such as area needed for maintenance paths, roads, fences and electrical equipment.

At the moment reliable, systematically collected, field data on the lifetime, energy yield and degradation of floating PV systems is lacking, due to the novelty of this application. In the absence of specific information, both PR and lifetime of floating systems were assumed equal to those of ground-mounted systems. These values for PR and lifetime are very uncertain and exert influence on the carbon footprint per kWh (see section 4.2).

The assumed PR and lifetime might be reasonable for the systems under evaluation. After all they are located on relatively small inland water bodies with very low wave height, have robust mounting systems and experience limited wind pressure due to the low tilt angle. Also, system lifetime and lifetime energy yield are essential design criteriums for any floating PV system. If either of these are substantially reduced, not only the carbon footprint per kWh but also the business case for the floating PV system will be heavily affected.[11] Nevertheless, systematic monitoring of the lifetime, energy yield and degradation of floating PV systems in various environments is needed to corroborate these assumptions.

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[11] The default Performance Ratio (PR) used of 0.80 could be considered conservative. In literature such as [1] it is suggested that floating PV systems may have a *higher energy yield* than ground-mounted PV systems, due to the cooling effect of the water body on which the system is installed. On the other hand, floating PV systems may also have *higher degradation losses* due to soiling (e.g., bird droppings), or due to wave-induced mismatch losses (that depend on system design and module movement). Both

4 CARBON FOOTPRINT ASSESSMENT

This chapter reports life cycle greenhouse gas emissions for both floating PV systems, per kWp and per kWh. The carbon footprint per kWh shows the estimated greenhouse gas emissions of the electrical energy generated by each type of system. Before that the carbon footprint per kWp is shown. This indicator has been added so that the reader can separately review the greenhouse gas emissions of the installations, without influence of the lifetime energy yield which is still rather uncertain and highly dependent on the location.

4.1 Carbon footprint per kWp

The carbon footprint in kgCO_2eq/kWp has been calculated for both floating PV systems, using LCI data from chapter 3.

potential effects are highly location dependent, if they occur. Neither of these potential effects have been taken into account, since there is no reliable measurement data available to quantify them.

Figure 4 below shows the greenhouse gas emissions in $kgCO_2eq/kWp$ electricity for floating PV systems FPV_A and FPV_B and for both the ground-mounted reference system GPV_op and GPV_ew. The carbon footprint of the systems is as follows: FPV_A: 1280 $kgCO_2eq/kWp$; FPV_B 1300 $kgCO_2eq/kWp$; and both GPV_ew and GWP_op: 1100 $kgCO_2eq/kWp$. The carbon footprint per kWp of both GPV systems is identical, since the only differences between these systems are their orientation, tilt and ground coverage ratio.

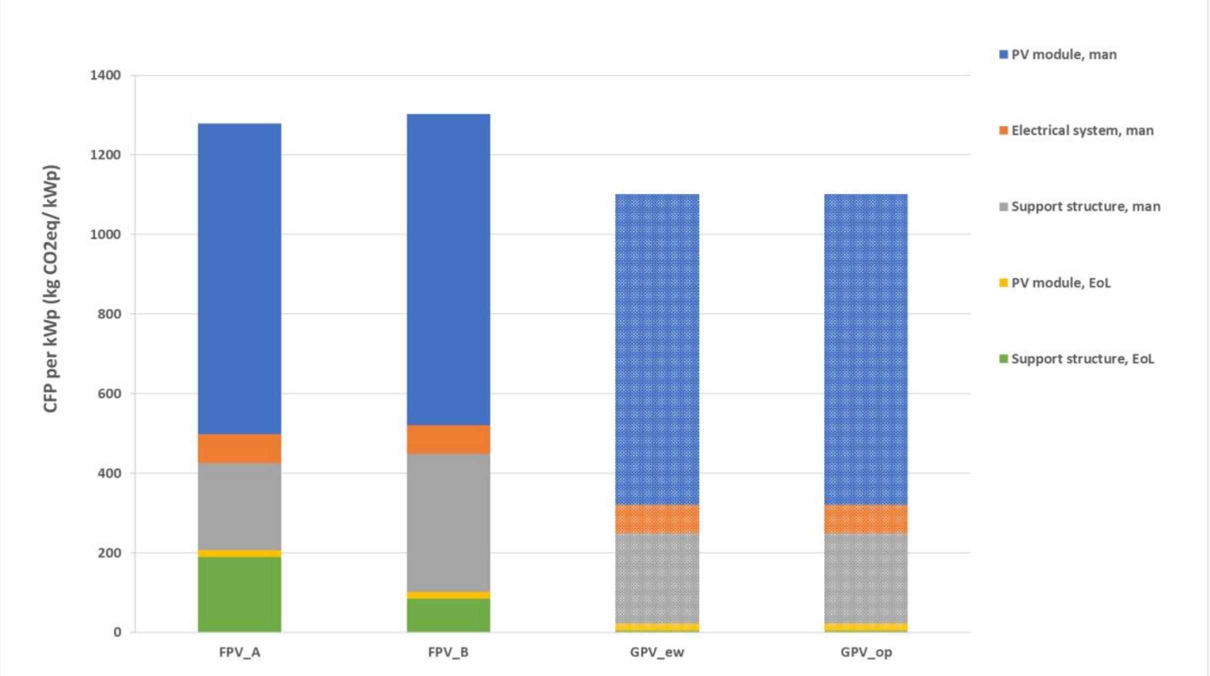

Figure 4: Carbon footprint per kWp of the floating PV systems and reference systems[12]

For all systems, the main contribution to the carbon footprint comes from the manufacturing of the PV module: 61% for FPV_A and 60% for FPV_B (72% for both GPV systems). The manufacturing of the support structure contributes 17% for FPV_A and 27% FPV_B (21% for both GPV systems). The third biggest contribution is from the end-of-life treatment of the support structure: 15% for FPV_A and 7% for FPV_B (1% for both GPV systems).

4.2 Carbon footprint per kWh

The carbon footprint in gCO_2eq/kWh has been calculated for both floating PV systems, using the carbon footprint per kWp from the previous section and the modelled lifetime energy yield from chapter 3. Figure 5 below shows the greenhouse gas emissions in $gCO_2eq/kWhac$ electricity for the PV systems. At the modelled reference location, the carbon footprint per kWh

[12] All systems use PERC glass-glass PV modules manufactured in China. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

of the two floating PV systems is as follows: FPV_A: 49 gCO_2eq/kWh; FPV_B 55 gCO_2eq/kWh. The calculated carbon footprint per kWh of the ground-mounted PV system with east-west orientation and low tilt angle (GPV_ew) is 46 gCO_2eq/kWh. For the ground-mounted system with optimum orientation and tilt (GPV_op) it is 38 gCO_2eq/kWh. 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. It is 3-4 times lower than the EU grid mix target for 2030, which is 176 gCO_2eq/kWh [12].

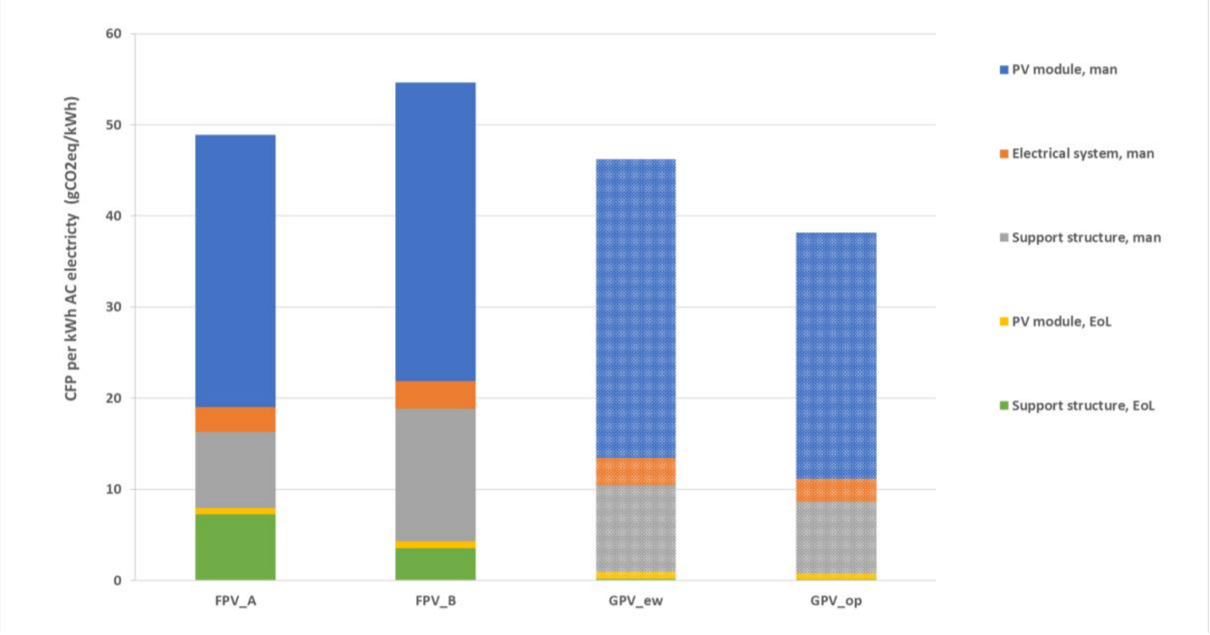

Figure 5: Carbon footprint per kWh AC electricity of the floating PV systems and reference systems.[13]

The lower carbon footprint of the GPV system with optimum orientation and optimum tilt (GPV_op) emphasizes the importance of a high energy yield for a low carbon footprint. 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.

How do these results compare to previously published LCA studies for floating PV systems?

Hayibo [11], [13] and Clemons [14] published LCA results on floating PV systems as part of a design study. Hayibo describes a concept for a foam-based flexible surface-mounted floating

[13] All systems use PERC glass-glass PV modules manufactured in China. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

PV modules that consists of SunPower SPR-E-Flex polymer PV modules backed with polyethylene foam. These modules would be deployed in Lake Mead (Arizona, USA). Clemons describes a concept for PV modules on pontoons, that consists of polycrystalline PV modules (13% efficiency) mounted on Highland Floats by ISCO Marine. These modules would be deployed on hydropower reservoirs in Thailand.

The carbon footprint reported for these systems is 11 gCO_2eq/kWh (Hayibo) and 73 gCO_2eq/kWh (Clemons). After correction for the estimated lifetime energy output per kWp the carbon footprint of these systems would be 28 gCO_2eq/kWh (Hayibo) and 102 gCO2eq/kWh (Clemons). The carbon footprint of the floating PV systems evaluated in this study (53 gCO_2eq/kWh) is in between these values. A direct comparison of these numbers is impossible due to the many differences in assumptions and the use of different sources for background data. Nevertheless, the difference in carbon footprint seems to be in line with the amount of material used for the support structures.

Which of the four systems is preferable from the point of view of carbon footprint will also depend on the lifetime energy yield that these PV systems can achieve in practice over their 30 year lifetime. The system proposed by Hayibo is the most vulnerable to module degradation since the PV modules have a polymer front and back sheet and are continuously immersed in water.[14] However, a final judgment requires systematic long-term monitoring of all systems under real-life conditions.

5 SENSITIVITY ANALYSIS

In this chapter the sensitivity of the carbon footprint of the floating PV systems for the lifetime of various components of the system is discussed (section 5.1). After that, the sensitivity for the three potential improvements is evaluated: the PV module carbon footprint (section 5.2); the carbon footprint of support structure manufacturing (section 5.3); the carbon footprint of the end-of-life treatment of the support structure (section 5.4). Finally, the effects of these three improvements are compared (section 5.5).

5.1 Sensitivity for component lifetime

In Figure 6 and Figure 7 one can see the sensitivity of the carbon footprint for the lifetime of the components and the total system, for the floating PV systems FPV_A and FPV_B respectively. For each component the carbon footprint is shown for the default component lifetime of 30 year and for shorter lifetimes of 20 and 25 year. In parallel to the shorter lifetime, we also assume an increased degradation rate, so that the average absolute yield loss over lifetime remains equal. Please note that for the inverter a lifetime of 15, 12.5 and 10 year is used, assuming one replacement of the inverter during the operation of the system.

The results for systems FPV_A and FPV_B are very similar. As can be expected a shorter lifetime of the system leads to a higher carbon footprint per kWh. Reduction of the system

[14] In fact, in the installation guide for this module the manufacturer Sunpower advises against immersion in water: “Certain operating environments are not recommended for SunPower modules and are excluded from the SunPower Limited Warranty. These include but are not limited to flooding, immersion in water or other fluids, (…)” [15]

lifetime from 30 to 20 years leads to an increase of the carbon footprint per kWh by 50%. 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 31% 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 expected, that from a carbon footprint perspective it could be worthwhile to replace components such as the inverter and the DC cables if this leads to a substantial increase of the energy yield. By contrast, earlier replacement of all PV modules or the total PV system is much less attractive because of the high contribution of the PV modules to the total carbon footprint.

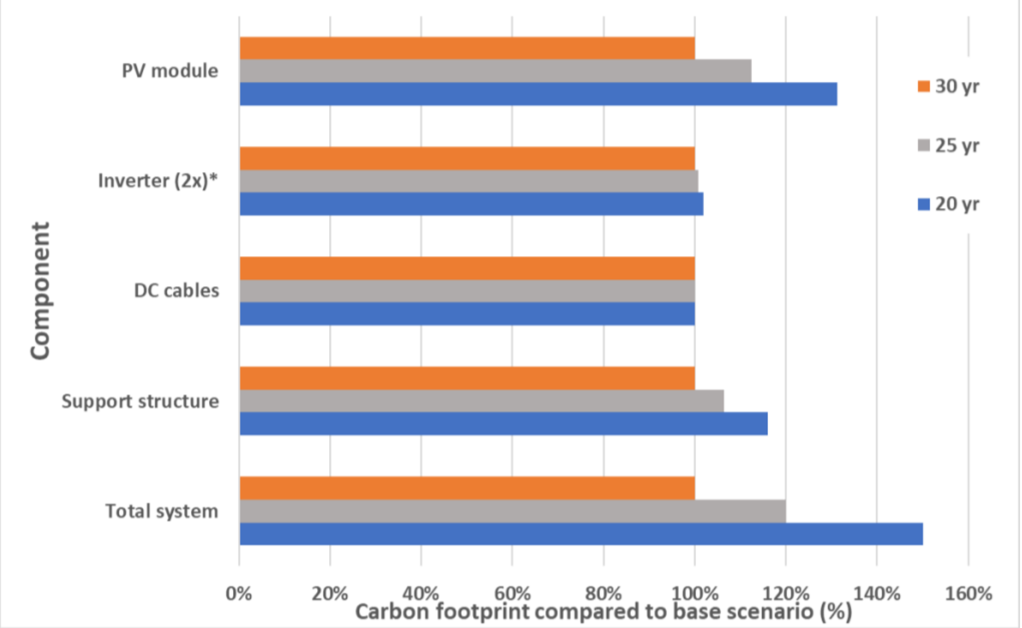

Figure 6: Sensitivity of CFP per kWh for lifetime of various components[15] (FPV_A).

[15] The default lifetime of 30 year is compared to lifetimes of 25 and 20 year. For the inverter one replacement during the operation of the system is assumed. This yields an inverter lifetime of 15, 12.5 and 10 year.

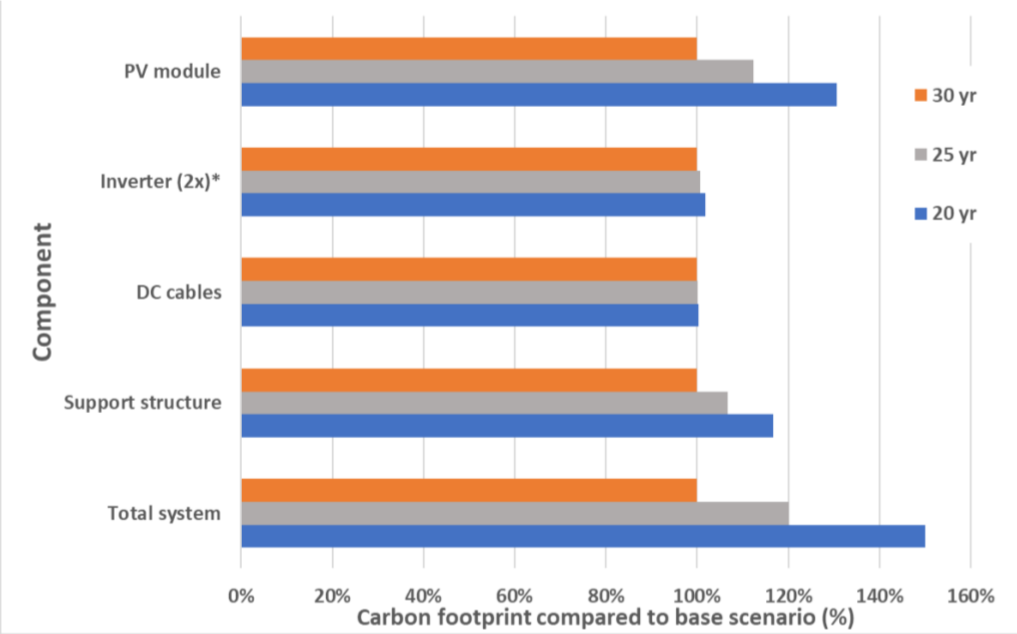

Figure 7: Sensitivity of CFP per kWh for lifetime of various components (FPV_B).

5.2 Sensitivity for PV module carbon footprint

In both FPV systems 20.5% efficient PERC glass-glass modules manufactured in China were used, with a PV module carbon footprint of 780 kgCO_2eq/kWp. What would happen to the comparison if PV modules with a substantially lower carbon footprint are used?

To evaluate this, the carbon footprint of the various systems was also calculated with an identical 20.5% PERC glass-glass module with frame, manufactured in Europe instead of China. The carbon footprint of this module is 460 kgCO_2eq/kWp**.** The effects on the carbon footprint of the various PV systems can be seen in Figure 8. When comparing this graph with Figure 5, it is clear that the overall carbon footprint of the PV system is reduced significantly, both in the floating PV systems (24-25%) and in the ground-mounted reference systems (29%).

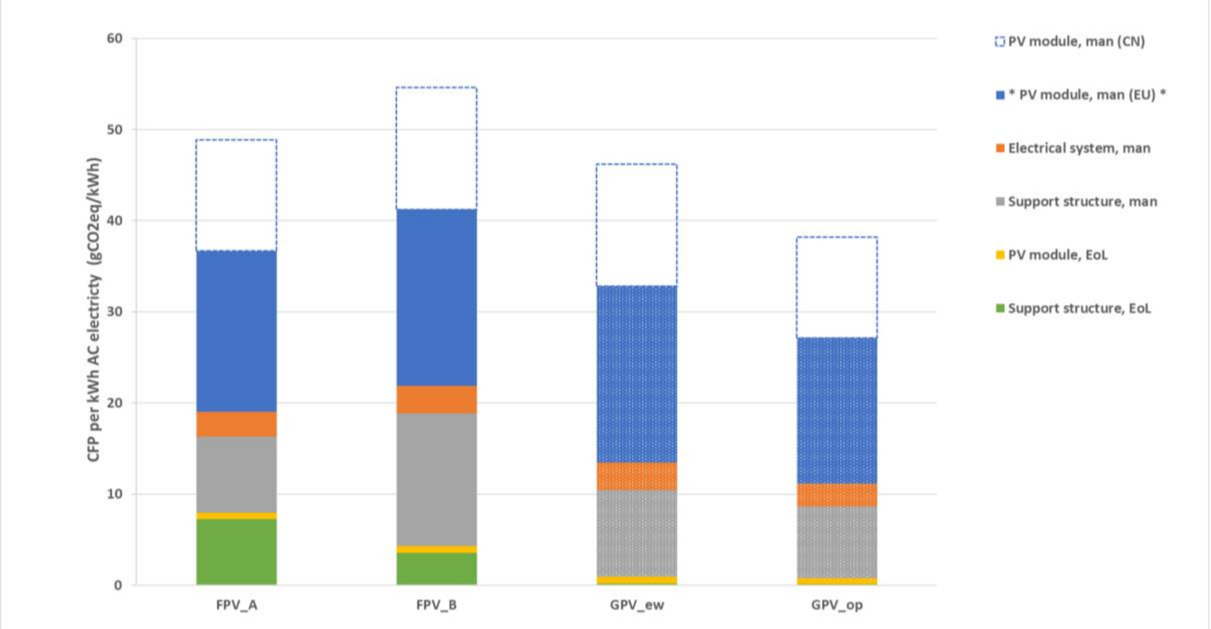

Figure 8: Carbon footprint per kWh AC electricity: PV module manufactured in EU.[16]

5.3 Sensitivity for support structure carbon footprint

Manufacturing of the support structure also contributes significantly to the carbon footprint of the floating PV systems. What would happen if we reduced the carbon footprint of the PV systems by using more recycled materials?

To evaluate this, the carbon footprint of the various systems was also calculated when the primary materials for the support structure (aluminium, concrete, galvanized steel, HDPE) are replaced by recycled materials (see Table 3). For floating system FPV_A the origin of the materials was also changed from Rest of World (high carbon intensity) to EU (lower carbon intensity).

The effects on the carbon footprint of the use of recycled materials in the support structures can be seen in Figure 9. When comparing this graph with Figure 5, it is clear that the overall carbon footprint of the PV system is reduced, both in the floating PV systems and in the ground-mounted reference systems. The biggest reduction is visible in floating system FPV_B (15%). This system has the highest proportion of steel[17] which is very carbon intensive to manufacture. Floating system FPV_A (7%) and the reference ground-mounted systems (13%) also show a significant reduction in carbon footprint, mainly through the replacement of steel and aluminium by recycled content.

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[16] All systems use PERC glass-glass PV modules. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

[17] This word was updated in the second version of the report to correct a minor error.

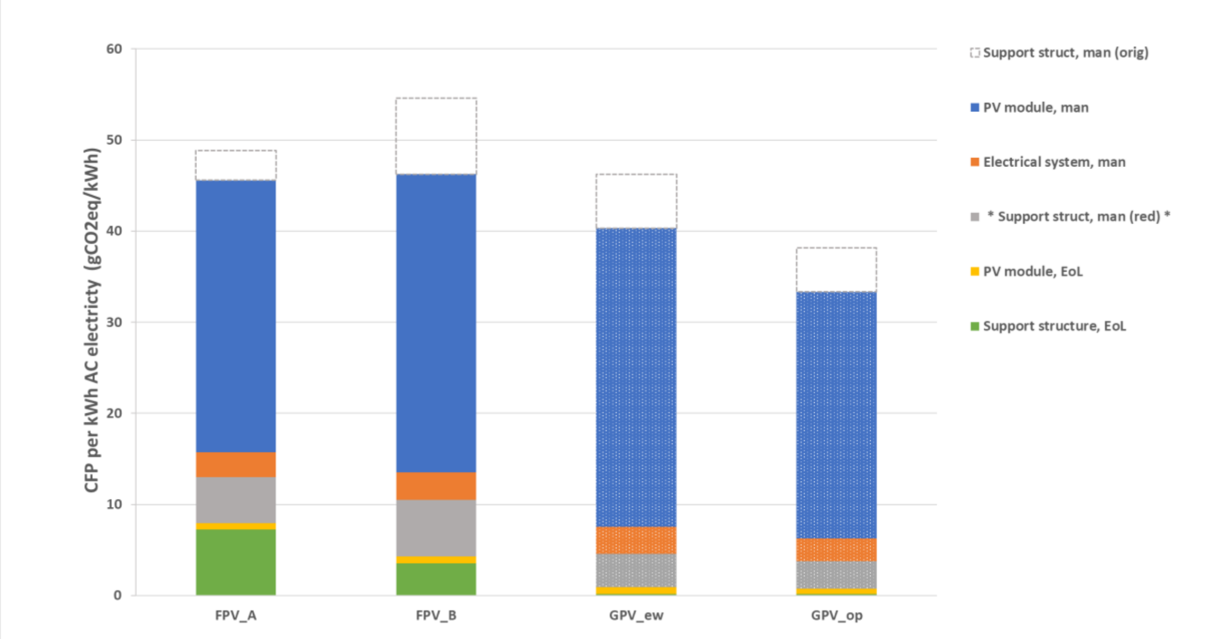

Figure 9: Carbon footprint per kWh AC electricity: support structure with recycled materials.[18]

5.4 Sensitivity for end-of-life treatment of support structure

The third process for which we evaluate the sensitivity is the end-of-life treatment of the support structure. What would happen if we reduced the carbon footprint of the PV systems by choosing an end-of-life treatment that is less carbon intensive?

To evaluate this, the carbon footprint of the various systems was also calculated with improved end-of-life treatment for the materials of the support structure (see Table 5). For metals and concrete recycling is already current practice, so for these materials the default end-of-life treatment can't be significantly improved. The option that remains is replacing incineration of HDPE (current practice) by recycling of HDPE. Note that the system owners already claim to use recycling as end-of-life treatment for HDPE.

The effects on the carbon footprint of the end-of-life treatment of the support structures can be seen in Figure 10. When comparing this graph with Figure 5, it is clear that the overall carbon footprint of the floating PV systems is reduced. The biggest reduction (11%) is visible in floating system FPV_A, which has the highest proportion of HDPE. Floating system FPV_B has a more limited reduction of the carbon footprint (5%). The reference ground-mounted systems have

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[18] All systems use PERC glass-glass PV modules manufactured in China. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

no option for improvement since their main materials (aluminium and galvanized steel) are already recycled in the default scenario.

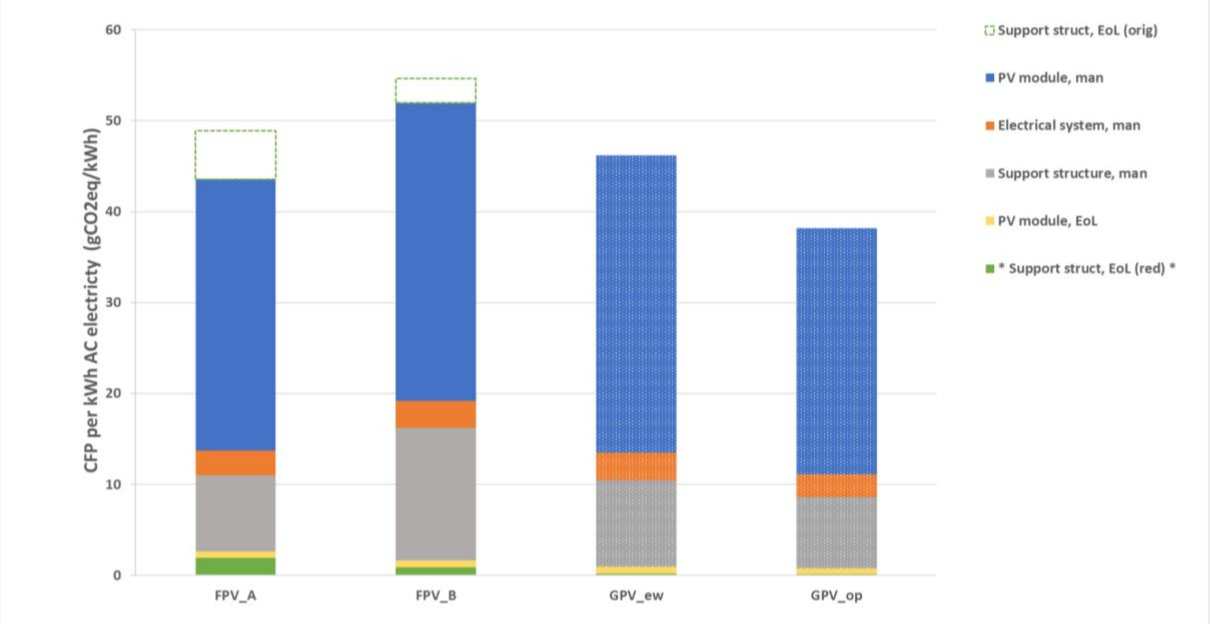

Figure 10: Carbon footprint per kWh AC electricity: support structure with improved end-of-life treatment.[19]

5.5 Sensitivity for three improvements compared

In the previous sections the impact of three improvements of the carbon footprint was evaluated:

- lower carbon footprint PV modules
- recycled materials for the support structure
- improved end-of-life treatment of the support structure.

How does the impact of these improvements on the carbon footprint of FPV compare?

The combined effects of these three improvements on the carbon footprint of the various PV systems can be seen in Figure 11. Since the improvements are independent their effects are added up. When comparing this graph with Figure 5, one can see that the three improvements combined lead to an overall carbon footprint reduction of respectively 43% (FPV_A) and 48% (FPV_B). For both ground-mounted systems the potential for reduction is 50%. In all cases the biggest contribution is from the choice of a PV module with a lower carbon footprint, followed

[19] All systems use PERC glass-glass PV modules manufactured in China. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

by the use of recycled content for the support structure. A substantial, but more limited contribution comes from the end-of-life scenario, namely replacement of HDPE incineration by HDPE recycling. Note that this is a measure that the owners of both floating PV systems already intend to take.

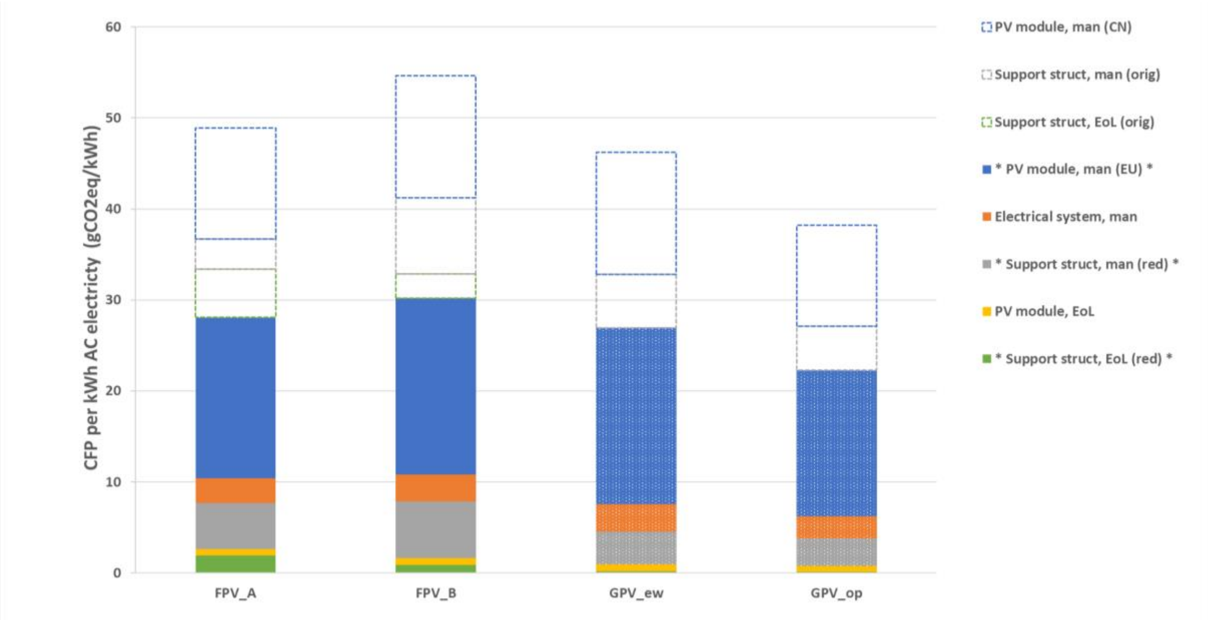

Figure 11: Carbon footprint per kWh AC electricity, three improvements compared: PV module manufactured in EU; support structure with recycled materials; improved end-of-life treatment support structure.[20]

[20] All systems use PERC glass-glass PV modules. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)
The following abbreviations are used: CFP: carbon footprint; EoL: end-of-life; ew: east-west; FPV: floating photovoltaic system; GPV: ground-mounted photovoltaic system; man: manufacturing; op: optimum orientation and tilt.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of the report was 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. LCI data was collected for two floating PV systems from two different suppliers: system FPV_A (HDPE/steel, south facing, 11° tilt) and system FPV_B (steel, east-west facing, 12° tilt). The carbon footprint per kWp electricity of the systems is approximately 1280 $kgCO_2eq/kWp$ (FPV_A) and 1300 $kgCO_2eq/kWp$ (FPV_B). The carbon footprint per kWh AC of the systems is approximately 49 gCO_2eq/kWh (FPV_A) and 55 gCO_2eq/kWh (FPV_B).[21]

For comparison, two ground-mounted systems were defined as reference, using background data only: GPV_ew (east-west facing, 12° tilt) and GPV_op (south orientation, 38° tilt)[22]. The carbon footprint per kWp for these systems is found to be 1100 $kgCO_2eq/kWp$. The carbon footprint per kWh AC of these systems is approximately 46 gCO_2eq/kWh (GPV_ew) and 38 gCO_2eq/kWh (GPV_op). 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 optimum orientation and tilt. 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 the carbon footprint of both floating PV systems is 7 times lower than that of the grid mix for this location in 2018 and 3-4 times lower than the EU grid mix target for 2030, which is 176 gCO_2eq/kWh [12].

As for ground-mounted PV systems, the manufacturing of the PV module has by far the largest contribution of the floating PV systems (60-61%. The manufacturing of the support structure contributes much less (17-27%). The third biggest contribution is from the end-of-life treatment of the support structure (7-15%). This means that the choice of PV module has a much larger impact on the carbon footprint of the PV system than whether the system is a floating or a ground mounted PV system.

The main uncertainty in these calculations are the lifetime and degradation of the floating PV systems. At the moment reliable, systematically collected, field data on the lifetime, energy yield and degradation of floating PV systems is lacking, due to the novelty of this application. In the absence of specific information, both PR and lifetime of floating systems were assumed equal to those of ground-mounted systems. This assumption needs to be verified by systematic

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[21] All systems use PERC glass-glass PV modules manufactured in China. (Location: Cologne (Germany), GHI: 1062 kWh/(m^2yr), module efficiency: 20.5%, bifaciality factor: 0, albedo: 0, degradation rate: 0.7%/year, PR: 0.80, lifetime: 30 year.)

[22] They are assumed identical to both floating PV systems apart from the support structure which was based on data from UVEK DQRV2:2022. The system parameters are identical to those for the floating PV (see previous footnote.)

data collection. Limited degradation of the PV modules is essential for a low environmental impact as well as for the economic feasibility.

6.2 Recommendations

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

- The outcome of this analysis suggests that, if the projected lifetime energy yield is achieved, 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 the 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.[23] 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 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 ecology.
- 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 currently lacking because floating PV is a relatively new application. This is also essential to corroborate the business case for floating PV.

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[23] 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.

- 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 be a good alternative for ground-mounted PV systems.

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6.3 Appendix A. LCI DATA

Table A1: LCI for the support structure of floating PV system FPV_A (HDPE).

	Name	Location	Unit	DE-FPV-Support-Structure (HDPE from RoW)	DE-FPV-Support-Structure (HDPE from EU + recycled content)	GeneralComment
	Location			DE	DE	
	Unit			m2	m2	
product	DE-FPV-Support-Structure (HDPE from RoW)	DE	m2	1	0	
	DE-FPV-Support-Structure (HDPE from EU + recycled content)	DE	m2	0	1	
materials	Concrete block, at plant/DE, U	DE	kg	45	45	Personal communication
	Polyethylene, HDPE, granulate, at plant/RER U	RER	kg	11.4	0.0	Personal communication
	Blow moulding (RoW)	RoW	kg	11.4	0.0	Personal communication
	Polyethylene, high density, granulate, recycled (Europe without Switzerland)	RER	kg	0.0	11.4	Personal communication (from EcoInvent 3.8)
	Blow moulding (RER)	RER	kg	0.0	11.4	Personal communication
	steel, converter, low-alloyed, at plant/kg/RER U	RER	kg	0.38	0.38	Personal communication
	Pig iron, at plant/kg/RER U	RER	kg		-0.32	Pig iron replaced by iron scrap
	Iron scrap, at plant/RER U	RER	kg		0.32	Pig iron replaced by iron scrap
	Aluminium alloy, AlMg3 at plant/RER U	RER	kg	0.57		Personal communication
	Aluminium scrap, new, at plant / RER, U	RER	kg		0.57	Personal communication
	Section bar extrusion, aluminium/RER, U	RER	kg	0.57	0.57	Adapted from "open ground construction on ground"
	Section bar rolling, steel/RER U	RER	kg	0.31	0.31	Adapted from "open ground construction on ground"
	Wire drawing, steel/RER U	RER	kg	0.053	0.053	Adapted from "open ground construction on ground"
	Zinc coating, pieces/RER U	RER	m2	0.0079	0.0079	Adapted from "open ground construction on ground"
	Zinc coating, coils/RER U	RER	m2	0.0055	0.0055	Adapted from "open ground construction on ground"
transport	Transport, transoceanic container ship/OCE U	GLO	tkm	137	0	Ras Tanura (SAr) - Rotterdam (NL): 12000 km
	Transport, freight, rail/tkm/RER U	RER	tkm	11.4	11.4	Assumption: HDPE transported 1000km
	Transport, freight, lorry fleet average/tkm/RER U	RER	tkm	6.9	6.9	Assumption: All materials transported 100km
	transport, barge/tkm/RER U	RER	tkm	13.8	13.8	Assumption: All materials transported 200km
information	total weight, Steel		kg	1.43	1.43	Sum from the inventory
	total weight, HDPE		kg	43.5	43.5	Sum from the inventory
	total weight, Aluminium		kg	2.15	2.15	Sum from the inventory
	total weight, Concrete		kg	45	45	Sum from the inventory

Table A2: LCI for the support structure of floating PV system FPV_B (Steel/HDPE).

	Name	Location	Unit	NL-FPV-Support-Structure	NL-FPV-Support-Structure (recycled content)	GeneralComment
	Location			NL	NL	
	Unit			m2	m2	
product	NL-FPV-Support-Structure (0% recycled HDPE)	NL	m2	1	0	
	NL-FPV-Support-Structure (recycled content)	NL	m2	0	1	
Materials	steel, converter, low alloyed, at plant/kg/RER U	RER	kg	16.2	16.2	Personal communication. Accounts for all the different steel structures like pipes, brackets and anchors, etc.
	Pig iron, at plant/kg/RER U	RER	kg		-14.1	Pig iron replaced by iron scrap
	Iron scrap, at plant/RER U	RER	kg		14.1	Pig iron replaced by iron scrap
	Polyethylene, HDPE, granulate, at plant/RER U	RER	kg	5.2		Personal communication
	Blow moulding (RER)	RER	kg	5.2		Personal communication
	Polyethylene, high density, granulate, recycled (Europe without Switzerland)	RER	kg		5.2	Personal communication (from EcoInvent 3.8)
	Blow moulding (RER)	RER	kg		5.2	Personal communication
	Section bar rolling, steel/RER U	RER	kg	13.7	13.7	Adapted from "open ground construction on ground"
	Wire drawing, steel/RER U	RER	kg	2.4	2.4	Adapted from "open ground construction on ground"
	Zinc coat, pieces {RER} | zinc coating, pieces| Cut-off, U	RER	m2	0.35	0.35	Adapted from "open ground construction on ground"
	Zinc coating, coils/RER U	RER	m2	0.24	0.24	Adapted from "open ground construction on ground"
transport	Transport, freight, lorry fleet average/tkm/RER U	RER	tkm	8.0	8.0	Assumption: All materials transported 300km
	Transport, freight, rail/tkm/RER U	RER	tkm	26.7	26.7	Assumption: All materials transported 1000km
information	total weight, Steel		kg	16.6	16.6	Sum from the inventory
	total weight, HDPE		kg	5.2	5.2	Sum from the inventory

Table A3: LCI for the support structure of ground-mounted PV system.

	Name	Location	Unit	open ground construction, on ground/m2/RER/I U	open ground construction, on ground/m2/RER/I U (recycled content)	GeneralComment
	Location			RER	RER	
	InfrastructureProcess			1	1	
	Unit			m2	m2	
product	open ground construction, on ground/m2/RER/I U	RER	m2	1		
	open ground construction, on ground/m2/RER/I U (recycled content)	RER	m2		1	
nature/resource	Transformation, from pasture, man made	RER	m2	4.72	4.72	Tucson Electric Power
	Transformation, to industrial area, built up	RER	m2	1.50	1.50	Literature and own estimations (UVEK)
	Transformation, to industrial area, vegetation	RER	m2	3.22	3.22	Literature and own estimations (UVEK)
	Occupation, industrial area, built up	RER	m2a	45.0	45.0	Assumed life time: 30 a
	Occupation, industrial area, vegetation	RER	m2a	96.6	96.6	Assumed life time: 30 a
materials	Aluminium, production mix, wrought alloy, at plant/kg/RER U	RER	kg	3.98		Literature and own estimations (UVEK)
	Aluminium, secondary, from new scrap0, at plant/RER U	RER	kg		3.98	Literature and own estimations (UVEK)
	Corrugated board, mixed fibre, single wall, at plant/RER U	RER	kg	8.64E-2	8.64E-2	Schwarz et al. 1992
	Polyethylene, HDPE, granulate, at plant/RER U	RER	kg	9.09E-4	9.09E-4	Literature and own estimations (UVEK)
	Polystyrene, high impact, HIPS, at plant/RER U	RER	kg	4.55E-3	4.55E-3	Schwarz et al. 1992
	Chromium steel 18/8, at plant/RER U	RER	kg	0.25	0.25	Literature and own estimations (UVEK)
	Reinforcing steel, at plant/kg/RER U	RER	kg	7.21	7.21	Literature and own estimations (UVEK)
	Pig iron, at plant/kg/RER U	RER	kg		-3.97	Pig iron replaced by iron scrap
	Iron scrap, at plant/kg/RER U	RER	kg		3.97	Pig iron replaced by iron scrap
	Concrete, normal, at plant/CH U	CH	m3	5.37E-4	5.37E-4	Fence foundation
	Section bar extrusion, aluminium/RER U	RER	kg	3.98	3.98	Estimation (UVEK)
	Section bar rolling, steel/RER U	RER	kg	6.15	6.15	Brunschweiler 1993
	Wire drawing, steel/RER U	RER	kg	1.06	1.06	Mesh wire fence
	Zinc coating, pieces/RER U	RER	m2	0.16	0.16	Estimation (UVEK)
	Zinc coating, coils/RER U	RER	m2	0.11	0.11	Fence
transport	transport, freight, lorry, fleet average/tkm/RER U	RER	tkm	0.22	0.22	Standard distance 50km
	transport, freight, rail/tkm/RER U	RER	tkm	5.14	5.14	Standard distances 200km, 600km
	transport, freight, light commercial vehicle/tkm/RER U	RER	tkm	1.14	1.14	100km to construction place
information	total weight, Steel		kg	7.46	7.46	Sum from the inventory
	total weight, HDPE		kg	9.09E-04	9.09E-04	Sum from the inventory
	total weight, Aluminium		kg	3.98	0.00	Sum from the inventory
	total weight, Concrete		kg	5.37E-04	5.37E-04	Sum from the inventory

Table A4: Overview of components of the electrical system, based on FPV_B data.

	Name	Location	Unit	NL-FPV-Electrical system	GeneralComment
	Location			NL	
	Unit			kWp	
product	NL-FPV-Electrical system	NL	kWp	1	
Materials	transformers high voltage [GLO]	GLO	kg	3.49E+00	Personal communication
	Inverter 500 kW	GLO	p	4.37E-03	Including one replacement (Personal communication)
	Cable, three conductor cable	GLO	m	3.36E-01	AC Cable (Personal communication)
	Cable, three conductor cable	GLO	m	3.64E+00	DC cable, length divided by 3 (Personal communication)

Table A5: Process descriptions of EoL treatments of various materials.

	Name	Location	Unit	EOL of Aluminium (recycling)	EOL of concrete (Recycling)	EOL of HDPE (Incineration)	EOL of HDPE (recycling)	EOL of Steel, Galvanised (Recycling)	GeneralComment
	Location			RER	RER	RER	RER	RER	
	Unit			kg	kg	kg	kg	kg	
product	EOL of Aluminium (Recycling)	RER	kg	1	0	0	0	0	collection and transport to recycling plant
	EOL of concrete (Recycling)	RER	kg	-	1	0	0	0	collection and transport to recycling plant
	EOL of HDPE (Incineration)	RER	kg	-	0	1	0	0	
	EOL of HDPE (recycling)	RER	kg	-	0	0	1	0	collection and transport to recycling plant + manufacturing of recycled HDPE - recycled HDPE
	EOL of Galvanised steel (Recycling)	RER	kg	-	0	0	0	1	collection and transport to recycling plant
Materials /resources	Waste polyethylene {Europe without Switzerland}| treatment of waste polyethylene, municipal incineration | Cut-off, U	RER	kg	0	0	1.00	0	0	From EcoInvent 3.8
	Polyethylene, high density, granulate, recycled {RoW}| polyethylene production, high density, granulate, recycled | Cut-off, U	RoW	kg	0	0	0	1.00	0	From EcoInvent 3.8
	Waste polyethylene, for recycling, sorted {RoW}| market for waste polyethylene, for recycling, sorted | Cut-off, U	RoW	kg	0	0	0	0	-1.06	From EcoInvent 3.8
transport	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U	RER	tkm	0.3	0.3	0.3	0.3	0.3	Assumption: All materials transported 300km
	Transport, freight train {Europe without Switzerland}| market for | Cut-off, U	RER	tkm	1.0	1.0	1.0	1.0	1.0	Assumption: All materials transported 1000km

6.4 Appendix B. Numerical Data of figures

This appendix contains the numerical data of the figures 4 to 11.

Table B1 / Figure 4. CFP in kgCO2eq/kWp.

CFP in kgCO2eq/kWp	FPV_A	FPV_B	GPV_ew	GPV_op
PV module, man	780.9	780.9	780.9	780.9
Electrical system, man	71.8	71.8	71.8	71.8
Support structure, man	218.5	347.3	227.2	227.2
PV module, EoL	17.9	17.9	17.9	17.9
Support structure, EoL	189.4	84.4	4.0	4.0
Total	1280	1300	1100	1100

Table B2 / Figure 5: CFP in gCO2eq/kWh AC electricity.

CFP in gCO2eq/kWh_ac	FPV_A	FPV_B	GPV_ew	GPV_op
PV module, man	29.9	32.8	32.8	27.1
Electrical system, man	2.7	3.0	3.0	2.5
Support structure, man	8.4	14.6	9.5	7.9
PV module, EoL	0.7	0.7	0.7	0.6
Support structure, EoL	7.2	3.5	0.2	0.1
Total	49	55	46	38

Table B3 / Figure 6:
Sensitivity of CFP per kWh for lifetime of various components (FPV_A).

System CFP versus lifetime (FPV_A)	30 yr	25 yr	20 yr
PV module	100%	112%	131%
Inverter (2x)	100%	101%	102%
DC cables	100%	100%	100%
Support structure	100%	106%	116%
Total system	100%	120%	150%

Table B4 / Figure 7:
Sensitivity of CFP per kWh for lifetime of various components (FPV_B).

System CFP versus lifetime (FPV_B)	30 yr	25 yr	20 yr
PV module	100%	112%	131%
Inverter (2x)	100%	101%	102%
DC cables	100%	100%	100%
Support structure	100%	107%	117%
Total system	100%	120%	150%

Table B5 / Figure 8:
Carbon footprint per kWh AC electricity: PV module manufactured in EU.

CFP in gCO2eq/kWh_ac	FPV_A	FPV_B	GPV_ew	GPV_op
PV module, man (CN)	12.2	13.4	13.4	11.1
* PV module, man (EU) *	17.7	19.4	19.4	16.0
Electrical system, man	2.7	3.0	3.0	2.5
Support structure, man	8.4	14.6	9.5	7.9
PV module, EoL	0.7	0.7	0.7	0.6
Support structure, EoL	7.2	3.5	0.2	0.1
Total (PV module, man (EU))	**37**	**41**	**33**	**27**
Total (original)	*49*	*55*	*46*	*38*

Table B6 / Figure 9:
Carbon footprint per kWh AC electricity: support structure with recycled materials.

CFP in gCO2eq/kWh_ac	FPV_A	FPV_B	GPV_ew	GPV_op
Support structure, man (orig)	3.3	8.4	5.9	4.9
PV module, man	29.9	32.8	32.8	27.1
Electrical system, man	2.7	3.0	3.0	2.5
* Support structure, man (red) *	5.1	6.2	3.6	3.0
PV module, EoL	0.7	0.7	0.7	0.6
Support structure, EoL	7.2	3.5	0.2	0.1
Total (recycled materials)	**46**	**46**	**40**	**33**
Total (original)	*49*	*55*	*46*	*38*

Table B7 / Figure 10:
Carbon footprint per kWh AC electricity: support structure with improved end-of-life treatment.

CFP in gCO2eq/kWh_ac	FPV_A	FPV_B	GPV_ew	GPV_op
Support structure, EoL (orig)	5.3	2.7	0.0	0.0
PV module, man	29.9	32.8	32.8	27.1
Electrical system, man	2.7	3.0	3.0	2.5
Support structure, man	8.4	14.6	9.5	7.9
PV module, EoL	0.7	0.7	0.7	0.6
* Support structure, EoL (red) *	1.9	0.9	0.2	0.1
Total (EoL support structure improved)	**44**	**52**	**46**	**38**
Total (original)	*49*	*55*	*46*	*38*

Table B8 / Figure 11:
Carbon footprint per kWh AC electricity, three improvements compared:
PV module manufactured in EU; support structure with recycled materials; improved end-of-life treatment support structure.

CFP in gCO2eq/kWh_ac	FPV_A	FPV_B	GPV_ew	GPV_op
PV module, man (CN)	12.2	13.4	13.4	11.1
Support structure, man (orig)	3.3	8.4	5.9	4.9
Support structure, EoL (orig)	5.3	2.7	0.0	0.0
* PV module, man (EU) *	17.7	19.4	19.4	16.0
Electrical system, man	2.7	3.0	3.0	2.5
* Support structure, man (red) *	5.1	6.2	3.6	3.0
PV module, EoL	0.7	0.7	0.7	0.6
* Support structure, EoL (red) *	1.9	0.9	0.2	0.1
Total (3 improvements)	**28**	**28**	**23**	**19**
Total (original)	*49*	*55*	*46*	*38*

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