North Sea Energy offshore system integration

D4.3

North Sea Energy 2023-2025

Carbon Footprint of Floating Solar

Navigating the North Sea transition!

For centuries, the North Sea has been a source of economic strength, ecological richness, and international cooperation. Always subject to change, yet steadfast as a connector of nations, cultures, and economies. Today, it once again takes center stage—this time as a lighthouse region for the transition to a sustainable, affordable, and reliable energy system. The North Sea Energy program marks an important step in this development.

North Sea Energy is a dynamic research program centered around an integrated approach to the offshore energy system. Its aim is to identify and assess opportunities for synergies between multiple low-carbon energy developments at sea: offshore wind, marine energy, carbon capture and storage (CCS), natural gas, and hydrogen. At the same time, the program seeks to strengthen the carrying capacity of our economy, society, and nature.

The offshore energy transition is approached from various perspectives: technical, ecological, societal, legal, regulatory, and economic. Our publications provide an overview of the strategies, innovations, and collaborations shaping the energy future of the North Sea. They reflect the joint efforts of companies, researchers, and societal partners who believe in the unique potential of this region as a hub for renewable energy and innovation.

What makes this program truly distinctive is not only its scale or ambition, but above all the recognition that we are operating in a dynamic field of research. The energy transition is not a fixed path, but a continuous process of learning, adapting, and evolving. New technologies, a dynamic natural environment, shifting policy frameworks, and changing societal insights demand flexibility and vision. Within this program, we work together to ensure that science and practice reinforce one another.

This publication is one of the results of more than two years of intensive research, involving over forty (inter)national partners. This collaboration has led to valuable insights and concrete proposals for the future of the energy system in and around the North Sea. All publications and supporting data are available at: https://north-sea-energy.eu/en/results/

We are deeply grateful to all those who contributed to the realization of this program. In particular, we thank our consortium partners, the funding body TKI New Gas, the members of the sounding board, the stakeholders, and the engaged public who actively participated in webinars and workshops. Their input, questions, and insights have enriched and guided the program.

At a time when energy security, climate responsibility, and affordability are becoming increasingly urgent, this work offers valuable insights for a broad audience—from policymakers and professionals to interested citizens. The challenges are great, but the opportunities are even greater. The North Sea, a lasting source of energy, is now becoming a symbol of sustainable progress.

With these publications, we conclude an important phase and look ahead with confidence to the next phase of the North Sea Energy program. In this new phase, special attention will be given to spatial planning in the North Sea, European cooperation, and the growing importance of security in the energy system of the future.

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Carbon Footprint of Floating Solar

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Executive summary

As part of the North Sea Energy 5 project, this report adds carbon footprints estimations to the footprints calculated in work package 4.2 in previous project versions. By means of life cycle assessment, carbon footprints of several floating solar archetypes and material choices were compared: high above sea level from steel or aluminium, just above sea level from steel or aluminium and membrane rings. Results showed that in most cases the structural material (metals and plastics) result in the largest contribution to the carbon footprint, followed by the PV panels and fuel use. The impact of aluminium structures is considerably higher than the impact of steel structures, even though large fraction of the aluminium used is recycled. This is largely due to the larger carbon footprint of aluminium with respect to steel. This, in turn, is caused by the electricity consumption necessary for the aluminium production process. The impact of the ring membrane structure is in between the aluminium structures and the steel structures. For the same metal type used in the structure, the high above sea level structures have a higher impact than the just above sea level structures due to higher material use. Steel high above sea level structures still have lower footprint than aluminium just above sea level structures and membranes.

Introduction

This report is drafted as part of the LCA studies carried out within Work package 4 of the North Sea Energy (NSE) 5 research program. The NSE research programme strives to outline routes to the energy transition in the North Sea that have positive societal and ecological impacts. It integrates knowledge from technological, economical, policy, participation and ecological and environmental expertise. While navigating the transition to a climate neutral energy system, insights into available technologies and innovations needs to exceed techno-economic information and for instance include estimations of the emission arising from the use of specific technologies.

For a range of energy transition technologies and infrastructures (platform electrification, hydrogen from different sources and locations, platforms and islands) the carbon footprints have been assessed in previous NSE projects. North Sea data for some technologies are still lacking. In particular, floating offshore solar farms become increasingly discussed as a way to mitigate the inherent intermittency of offshore wind electricity generation. However, different designs are still under investigation for this emerging technology, in particular under offshore conditions. As a consequence, little is known about the carbon footprint of floating offshore solar.

1.1 Aim and Research questions

This study aims to evaluate and compare the carbon footprint of different hypothetical offshore floating solar farms designed to operate in the North Sea. The main research question is which life cycle greenhouse gas emissions are associated with floating solar farms. To answer this question, first the energy and material demand for different types of floating solar farms have to be inventoried. Based on these data the carbon footprints of different types can be assessed and compared. Based on the contribution to the carbon footprint, options for emission reductions can be identified.

Results of this report can be used in hub design decisions as well as support for technology developers and project developers. The material balance compiled in this report will also serve as input to a material flow assessment, that is also part of this work package. Floating solar farm types, material balances, and installation as well as maintenance trips have been defined by DMEC.

1.2 Outline

Chapter 2 outlines the methodology, life cycle assessment, the data gathering approach and the inventories compiled. Chapter 3 describes the results. Chapter 4 discusses the preliminary results obtained, results obtained after a round of interviews with technology developers, possible lessons learned and sensitivity analysis with regards to potential future developments. Based on interviews conducted during the NSE4 project, calculations for fuel consumption have been updated. Additionally, sensitivity analysis using future energy mixes have been added databases have been updated and waste modelling has been improved based on internal suggestions. The sections in methodology, results and discussion, are indicated as ‘updates’ in the respective headings. In chapter 4 conclusions and recommendations are discussed.

2 Method

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a method to systematically quantify and compare the effects of a product, system, service or geographical/organizational entity. As the name suggests, an important characteristic of LCA is that it takes into account the complete life cycle of a product (cradle-to-grave) from resource extraction to waste treatment, including transport in between. In some cases (e.g. if the environmental performance of a company making consumer products is assessed), the analysis is constrained to the production phase (cradle-to-gate). Another important characteristic of LCA is that a wide range of environmental problems can be addressed, such as climate change and toxicity to humans or ecosystems. This way, trade-offs between life cycle stages and/or environmental problem areas are identified. Finally, LCA is generally considered a comparative rather than an absolute tool. LCA is conducted in four interrelated steps: 1) Goal and scope definition; 2) life cycle inventory; 3) impact assessment; 4) interpretation and conclusions (ISO 14040/44). Each of these steps is described in more detail below for the floating solar farms considered in this study.

2.2 Goal and Scope

In the goal and scope definition, where the products to be compared are defined, the functional unit, the type of LCA, system boundaries, and impacts and impact assessment methodology are set. A functional unit (FU) is the unit of comparison to which all flows in the inventory are related. It is important that the functional unit is defined in such way that all systems under comparison fulfil the same function. For comparison of natural gas production, this is generally 1 m3 of gas, for hydrogen production 1 MJ of hydrogen and for electricity generation 1 kWh.

2.2.1 Goal and Functional unit

The goal of this study is to compare the carbon footprint of five different offshore floating solar farms over their life cycle, but excluding electricity generation. The functional unit is this study is the provision of a specified amount of power (1kWp) at the moment of installation. All the floating solar farms considered here are designed for the production of 15 MW. Each floating solar farm type has a different design, as they are composed of a different number and types of modules according to the design considered. The results have been scaled linearly with the designed power output to obtain the values for 1kWp.

2.2.2 Scope

The geographic scope is the North Sea. The temporal scope is a full life cycle starting between 2020 and 2030, but assuming current market relations. With an estimated life time of 25 years as defined in WP1 of the program. This is in line with the lifetime of commercially available PV panels.

2.2.2.1 Structure selection

Floating solar farms are composed of several modules attached to each other to form a structure. These modules are made of a steel/aluminium beams and plastic floater or, in the case of the ring membrane, by a steel ring with a plastic membrane stretched across it. The structure is provided with steel walkways to reach to the single PV panels for maintenance and extra space for the installation of the inverters. The PV panels are installed on the modules by means of a supporting frame or glued on a membrane. The PV panels are interconnected using MC4 junction box connectors and standard electric cables (weight ~60g/m) to form arrays of 500 kW. Each array is connected to a 500 kW inverter using standard electric cables (weight ~60g/m). The floating structures are then anchored to the sea bottom using mooring lines. Signalling buoys are installed around the structure as well as on the mooring lines. Three archetype structures have been selected based on literature review and market exploration (World Bank Group, ESMAP, and SERIS 2019b; 2019a; Deign, Linden, and Hartung 2022), to be suitable for offshore floating solar, all sized for the production of 15 MW. Sketches of these types are included in the Appendix A1, characteristics are described below.

- High above sea level structures are structures where the PV panels are installed several meters above the sea level and therefore are not reached by seawater. These structures are composed by 143 modules of two different types (Module 1 and Module 2) tied together, each containing 288 PV panels, in this design type, the modules are disposed on a grid of 13x11. Modules 1 have tall floaters that keep the structure elevated from the sea, Modules 2 do not have floaters and are supported by modules 1. See Figure 5 in Appendix A1 for a diagram showing the disposition of the modules and Figure 6 displaying a sketch of Module type 1.
- Just above sea level structures are structures where the PV panels are installed close above the sea level and therefore can be washed over by the seawater. These structures are composed of 1736 modules each containing 24 PV panels disposed on a grid of 31x56. All the modules in this design contain two small floaters. See Figure 7 in Appendix A1 displaying the disposition of the modules and Figure 8 displaying a module sketch.
- Membrane ring structures are also structures floating directly on the surface of the seawater, composed by 11 ring modules formed by a plastic membrane spanned across a steel ring, each membrane supporting 3716 PV panels. No floaters are needed in this configuration as the ring membrane modules float by design. Eleven rings are needed to compose one system of 15 MW, see Figure 9 in Appendix A1 displaying the module setup and Figure 10 displaying a module sketch.

The high above sea level and just above sea level structures have been calculated for both steel and aluminium, so that in total five different structures are analysed. All the platforms were sized for 15 MW systems, equipped with silicon glass backsheet panels, MC4 Junction boxes, interconnecting cables, 30 inverters of 500 kW and cables connecting to the inverter. Table 1 gives an overview of the number of modules and PV for each structure.

Table 1: Overview of floating platform construction for a 15 MW structure (data generated by DMEC)

	# of modules types	# of modules	Power per module	Comment
High above Sea (Aluminium and Steel)	2	42 Module 1, 101 Module 2	Total power per module (module 1 and Module 2): 104 kW (288 PV panels per Module)	Modules 1 (with floaters) support Modules 2 (without floaters). See Figure 2 for further explanation.
Just above sea (Aluminium and Steel)	1	1736 Modules	Total power per module: 8.64 kW (24 PV panels per module)	All the modules contain floaters
Ring membrane	1	11 Ring	Total power per module: 13338 kW (3716 PV panels per module)	

2.2.3 System Boundaries

As already mentioned, this study covers the full life cycle of the floating structures, from material extraction to structure decommissioning. In particular it includes:

- the amount (in mass or volume) and type of material used over the life cycle of the structure: steel, aluminium, plastic, etc.
- the manufacturing of the floating solar structure
- the manufacturing and mounting of the PV system (panels, junction boxes, interconnecting cables, and inverters)
- the amount and type of fuel used for transporting the materials and/or structure components before and after its life at sea, but also for construction, installation, dismantling and for operation and maintenance. These are likely influenced by the type of vessel, the transport distance, the amount of material to be transported and the type of construction, installation and dismantling and removal activity. In the case of the maintenance, only vessel use has been accounted for but the operations carried out on the structures themselves are excluded, as no reliable estimation of energy and material use for this purpose was found at the time of writing.

The electricity production of the PV panels is out of scope, as these are expected to be related more to local conditions than to the type of structure. Secondary infrastructure such as factories, vessels or cranes is not included in the analysis. For both types of data (materials and fuels), the data gathering approach is described in more detail in the next section.

2.3 Inventory

Inventory refers to the data gathering phase, were all inputs and outputs of the product system are compiled. These encompass resource extractions as well as emissions into the environment and are summarized under the term interventions. This report focusses on the interventions that have an influence on the emissions of greenhouse gases related to the life cycle of the floating solar structures, i.e. the material production and use for the construction of the structures, and the fuel burned during the operations of installation, maintenance and decommissioning.

In this study, foreground data, i.e. material needs for each of the structures, fuel consumption for transport, construction, installation, maintenance and dismantling, have been gathered in cooperation with DMEC. DMEC developed designs for the floating solar structures archetypes, to estimate material consumption and fuel use for installation, decommissioning and maintenance. The inventory of materials for the considered offshore floating solar designs (see section 2.3.3) was created based on the generic designs of DMEC rather than on actual pilot structures available at the market (and/or near-market-ready). This provides a more comprehensive overview of the possible offshore floating solar designs that may be present at the market in 2030, 2040 and 2050. The generic designs considered in the study (see below) were developed by DMEC (outside of the scope of this study) using 3D Design software. The systems are not optimised in order to have a more generic, not design/pilot-specific characteristics but yet to reflect the future scenarios considered. Background data, i.e. the environmental profiles related to these materials and fuels, are taken from the ecoinvent 3.8 cut-off database (Wernet et al., 2016). In cut-off processes are modelled up to the point of lowest value, potential recycling burdens and advantages are allocated to the next life cycle – as required in many guidelines, for instance environmental footprints. Wherever possible the “market for” processes have been selected.

2.3.1 Materials and Manufacturing

For all structures, it was assumed that the single parts were manufactured and assembled on land and then towed and anchored on site by means of tugboats and crew transfer vessels. The manufacturing process of the metal parts was accounted for by means of the ecoinvent process “Metal working, average for steel (or aluminium) product manufacturing”.

Each floating structure carried several PV panels, inverters and cabling in order to generate electricity. The PV panels modelled for this purpose are standard Silicon glass back sheet panels with an efficiency of 19.79%, as described in (Müller et al. 2021). A more detailed description of the inventory of the Silicon panels is given in section 2.3.4.

2.3.1.1 Update to material use modelling

During the NSE5 project and update of the ecoivent database became available (v. 3.10 instead of v. 3.08) and has been used in the updated calculations. Additionally, following an internal review on the ecoinvent processes used to model the materials in this study, the ecoinvent process “Metal working, average for steel (or aluminium) product manufacturing” has been modified assuming a 5% metal waste (and consequent input) during the metal working process. In the previous calculations, the processing waste of the ecoinvent card had been neglected as the original ecoinvent input (i.e. 22.7% waste during the metal processing) was deemed too high.

2.3.2 Update with prospective scenarios

To give an insight on how the carbon footprint of the different floating solar structures will change in the future, the carbon footprint of the production of aluminium and steel were extracted from the integrated assessment model (IAMs) IMAGE (Stehfest et al., 2014) for two scenarios so called SSP2- Base and SSP2-RCP1.9 for the years 2030 and 2050. These two scenarios have been chosen as they portrait two different future developments based on the extrapolation from historical developments: in the case of IMAGE-SSP2- Base, no new climate policies are implemented leading to an average global temperature rise of ~3.5 ^{o}C, while in the case of IMAGE-SSP2- RCP 1.9 the Paris Agreement objectives are met, leading to an average global temperature rise of ~1.2-1.4 ^{o}C. These data were the used to recalculate the carbon footprint of the structures in the year 2030 and 2050.

2.3.3 Fuel use

The fuel consumption for installation, operation and maintenance and decommissioning has been based on vessel use based on specifications provided by DMEC. All the considered vessels run on Marine Diesel Oil (MDO). The installation, operation, maintenance and decommissioning procedures were established for the various offshore floating solar designs based on the state-of-art sector knowledge available at DMEC and with consultation with external experts on these procedures (including WaveEC Offshore Renewables, Portugal). The fuel consumption of all vessels was modelled using the global market for ecoinvent process “Diesel, burned in fishing vessel”.

2.3.3.1 Installation and decommissioning

The number of vessels necessary to tow the structures in place and the towing speed was calculated based on the expected drag generated by the shape and size of the transported modules. The results of these calculation were provided by DMEC and can be seen in Table 2. Once the vessel configuration per structure was determined, the fuel consumption was calculated based on the distance from shore, i.e. 100 km, and the vessel speed and the fuel consumption per vessel type. The distance of 100 km was chosen as a distance to Hub North in Work Package 1 Hub Design and employed here to consider a worst case situation. The fuel consumption displayed in Table 3 is given at the top speed of the vessels. This is likely to be higher than the fuel consumption at the specified towing speed calculated for the installation of the structures considered in this study but has been used as a worst case scenario as no other data were available. The fuel consumption per km at top speed (see table 2), has been multiplied with the distance and number or trips to arrive at a fuel consumption per activity. A detailed example of fuel consumption calculation based in these data is given in Section 2.3.2.1. The fuel consumption for the decommissioning was considered to be the same as for the installation.

Table 2: Overview of the vessel use for the installation (and decommissioning) of the different floating solar platforms of 15 MW.

	Vessel type	Speed	# of trips
High above Sea (Alu and Steel)	2 Large tug boats 1 Small tug boat	7.4 km/h	12
Just above sea (Alu and Steel)	3 small tug boats	14.8 km/h	14
Ring membrane	2 Large tug boats 1 Small tug boat	14.8 km/h	11

Table 3: Overview of the vessels used during installation and relative fuel consumption (Information provided by DMEC)

	Fuel consumption [L/h]	Fuel consumption [L/km]
Crew Transfer Vessel (CTV)	320 L/h (@ 26 km/h) 130 L/h (stationary)	N.A.
Large Tug Boat (100T Tug)	700 L/h (@ 26 km/h)	27.2 L/km (@ 26 km/h)
Small Tug Boat (40T Tug)	360 L/h (@ 20 km/h)	17.2 (@ 20 km/h)

2.3.3.2 Operation and Maintenance

As initial assumption, operation and maintenance has been assumed to be the same for all the floating structure types. DMEC provided a detailed overview of the trips and actions needed for OM during the whole life time of the floating structures, see Table 4. Operation and Maintenance tasks decrease during the lifetime of the structure: Initially OM trips are planned more frequently to ensure that the systems are working as expected and to prevent unnecessary damages early on in the deployment's lifecycle, and gradually reduced towards the end of the lifetime as it will become redundant to carry out larger repairs and frequent monitoring at this stage.

Table 4: Overview of OM for the different floating structures during the entire lifetime

Period	Scheduled yearly maintenance	Cleaning yearly	Emergency repairs yearly	Large vessel repair yearly
2030-2039	6 trips with 2 CTVs[1]	4 trips with 2 CTVs[1]	2 trips with 1 CTV[1]	1 trips with 1 40T[2] tug
2040-2049	4 trips with 2 CTVs[1]		2 trips with 1 CTV[1]	1 trips with 1 40T[2] tug
2050 - 2055	3 trips with 2 CTVs[1]		2 trips with 1 CTV[1]	1 trips with 1 40T[2] tug

[1] Crew Transfer Vessel
[2] Small tug boat

The fuel consumption for operation and maintenance has been calculated in the same manner as for the installation. i.e. based on the distance from shore (100 km), the fuel consumption at top speed and the number of trips per year. It was assumed that for operation and maintenance, the vessels could travel at top speed as no towing was necessary. The total fuel consumption over a lifetime of 25 years amounted to 489000 L of diesel for a 15 MW floating solar farm. This resulted in 33 L/kWp.

2.3.3.3 Decommissioning and End of Life

Decommissioning operations, and therefore energy consumption, is considered equal to the installation, since it requires similar processes done in an inverse order.
Due to the uncertainties relative to the future recycling process, this study assumed that the metal recycling and PV panel recycling would happen onshore by third parties. For this reason, the lifecycle considered here has been cut off at the decommissioning phase of the floating structures and the burdens and benefits associated with the recycling processes have been excluded from the system boundaries.

2.3.3.4 Updates to fuel use estimates (interviews)

In order to achieve a more accurate picture of the operations and fuel consumption occurring during installation, decommissioning and maintenance, DMEC carried out extensive interviews with commercial parties operating in the floating solar sector. Based on the outcomes of these interviews, the operations and vessel use during installation, operation and maintenance and decommissioning has been modified, as reported in the following paragraphs.

Installation and decommissioning

The installation of the High above sea level and Just above sea level structures required the use of a single large tug boat of 150T with the assistance of two smaller tugboats waiting at the installation location. Each trip of could install 1.1 MW. Updated data are shown in Table 5. As in the previous calculations, it was estimated that while the high above sea level structure could be tawed at 4kn, the just above sea level structure could be tawed at 8kn. Furthermore, an estimate of energy consumption due to loitering during the installation process was added. As in the previous estimates, it has been assumed that the fuel consumption during decommissioning is the same as during the installation process.
From the interviews, it also appeared that the ring membrane structure was unlikely to be further deployed commercially, therefore no new data emerged for this structure.

Table 5: Updated overview of the vessel use for the installation (and decommissioning) of the different floating solar platforms of 15 MW resulting from the interviews with companies operating in the field

	Vessel type	Speed	# of trips
High above Sea level (Alu and Steel)	1 Large tug (150T) boat tawing	7.4 km/h	14
	1 Large tug boat sailing back	25.93 km/h	14
	2 Small tug boats (moving in and then waiting at location)	20.37 km/h	2
	Tug (large or small) loitering	Stationary, 10 hours	14
Just above Sea level (Alu and Steel)	1 Large tug (150T) boat tawing	14.8 km/h	14
	1 Large tug boat sailing back	25.93 km/h	14
	2 Small tug boats (moving in and then waiting at location)	20.37 km/h	2
	Tug (large or small) loitering	Stationary, 10 hours	14

Table 6: Updated information on vessels used during installation (and decommissioning) and relative fuel consumption (Information provided by DMEC)

	Fuel consumption [L/h]	Fuel consumption [L/km]
Crew Transfer Vessel (CTV)	320 L/h (@ 26 km/h)	N.A.
Crew Transfer Vessel (CTV) loitering	130 L/h	N.A
Large Tug Boat (150T Tug)	906 L/h (@ 26 km/h)	N.A
Small Tug Boat (40T Tug)	360 L/h (@ 20 km/h)	17.2 (@ 20 km/h)
Tug (large or small) loitering	471 L/h	N.A

Operation and Maintenance

Based on the interview results, trips for to operation and maintenance have been considerably reduced. Table 7 gives an overview of the updated O&M trips during the whole lifetime of the floating solar structures. From the interviews it also emerged that several technologies are being investigated to further reduce the cleaning efforts required during the lifetime of the floating solar structures, e.g. the installation of cleaning robots (including a desalination unit) on the solar farm itself. This is particularly attractive to avoid the transport of freshwater from shore during cleaning operations. Unfortunately, these technologies are still too experimental at the stage of writing to provide a reasonable energy consumption estimate and the use of such robots has not been included in this inventory. Also in this instance, no difference in O&M operations has been assumed between the different structure types.

Table 7: Updated overview of OM for the different floating structures during the entire lifetime

Period	Scheduled maintenance	Cleaning yearly	Large vessel repair (lifetime)
2030-2039	2 trips with 2 CTVs	2 trips with 2 CTVs	
2040-2049	2 trips with 2 CTVs	2 trips with 2 CTVs	1 trips with 1 40T[2] tug
2050 - 2055	2 trips with 2 CTVs		

2.3.4 Inventory Tables - Floating structures

The inventory of the different floating farms is structured as follows:

- At first the fuel consumption is presented. This is the same for installation and decommissioning, for high above sea structures of both material types and both just above sea types. The fuel for maintenance is the same for all types of solar farms.
- The inventory for material use is presented for each type of solar farm: Initially the materials for the construction of a single module are presented and then the inventory for the production of a 1 kWp floating solar structure are presented.

2.3.4.1 High Above Sea level – Aluminium

The following tables include the material and fuel use for the High above sea floating structure. Initially the amount to build a single module are presented and then the inventory for 1kWp structure are given in Table 10. Different types of modules are needed (Module 1 and Module 2) in order to minimise the structural materials needed to support the loads.

Table 8: Inventory for Module 1 for high above sea structure, Aluminium, based on DMEC calculations. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Module 1 - High above sea level_Aluminium	p	1	
Inputs			
Aluminium alloy, AlMg3	kg	992	Space frame connectors. 5083 aluminium alloy is an aluminium–magnesium alloy with magnesium and traces of manganese and chromium. It is highly resistant to attack by seawater and industrial chemicals.
Aluminium alloy, AlMg3	kg	3560	Floater shaft
Polyethylene, high density, granulate	kg	2740	Floater
Extrusion, plastic pipes	kg	2740	Floater. Production process, geography Europe
Aluminium alloy, AlMg3	kg	3840	Beam horizontal
Aluminium alloy, AlMg3	kg	800	Beam vertical
Steel, low-alloyed	kg	672	Cable short
Steel, low-alloyed	kg	288	Cable long
Si, Glass backsheet module integration_CN_NSE5	kWp	104	See relative inventory
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	104	MC4 junction box connectors and cabling between panels. See Table 19
Grid connection_Si system_NSE5	kWp	104	See Table 20
Aluminium alloy, AlMg3	kg	720	PV supporting frame 1
Aluminium alloy, AlMg3	kg	648	PV supporting frame 2
Aluminium alloy, AlMg3	kg	972	Walkway
Metal working, average for aluminium product manufacturing	kg	11532	sum of mass of all al components. Process modified by eliminating Al input. Geography: 'Rest of the world'[A], production process

A: rest of the world is chosen when none of the regions available in ecoinvent matches for the region of interest, and represents an average production in all the other regions.

Table 9: Inventory for Module 2 for high above sea structure, Aluminium. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Module 2 - High above sea level_Aluminium	p	1	This is a "piece", i.e. a single module
Inputs			
Aluminium alloy, AlMg3	kg	992	Space frame connectors. 5083 aluminium alloy is an aluminium–magnesium alloy with magnesium and traces of manganese and chromium. It is highly resistant to attack by seawater and industrial chemicals.
Aluminium alloy, AlMg3	kg	3840	Beam horizontal
Aluminium alloy, AlMg3	kg	800	Beam vertical
Steel, low-alloyed	kg	672	Cable short
Steel, low-alloyed	kg	288	Cable long
Si, Glass backsheet module integration_CN_NSE5	kWp	104	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	104	See Table 19
Grid connection_Si system_NSE5	kWp	104	See Table 20
Aluminium alloy, AlMg3	kg	720	PV supporting frame 1
Aluminium alloy, AlMg3	kg	648	PV supporting frame 2
Aluminium alloy, AlMg3	kg	972	Walkway
Metal working, average for aluminium product manufacturing	kg	7972	sum of all Al components. Process modified by removing the Al input. Geography: 'Rest of the Word', production process

Table 10: Inventory for the complete lifecycle of the Aluminium High above sea floating structure, for 1 kWp. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
High above sea level Al complete structure	kWp	1	
Inputs			
Module 1 - High above sea level_Aluminium	p	0.0028	See Table 5
Module 2 - High above sea level_Aluminium	p	0.00673	See Table 6
Polyethylene, high density, granulate	kg	11.86	Mooring lines
Polyethylene, high density, granulate	kg	1.04	Buoys in mooring lines
Polyethylene, high density, granulate	kg	0.139	Signalling buoys
Extrusion, plastic pipes	kg	13	Extrusion of all materials above
Metal working, average for steel product manufacturing	kg	10.4	Process modified by removing the steel input. Geography: 'Rest of the World', production process
Steel, low-alloyed	kg	10.4	Anchors
Epoxy resin, liquid	kg	0.39	Steel coating assumed as 2% of steel mass. Geography: Europe
Fuel burned for maintenance	MJ	1250	
Fuel burned for installation and decommissioning	MJ	1436	

2.3.4.2 High above sea level - Steel

The following tables include the material and fuel use for the High above sea floating structure. Initially the amount to build a single module are presented and then the inventory for 1kWp structure are given in Table 13.

Table 11: Inventory for Module 1 for high above sea structure, Steel. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Module 1 - High above sea level_Steel	p	1	This is a “piece”, i.e. a single module
Inputs			
Steel, low-alloyed	kg	990.25	Space frame connectors.
Steel, low-alloyed	kg	3553.72	Floater shaft
Polyethylene, high density, granulate	kg	2740	Floater
Extrusion, plastic pipes	kg	2740	Floater. Geography: Europe, production process
Steel, low-alloyed	kg	3833.23	Beam horizontal
Steel, low-alloyed	kg	798.59	Beam vertical
Steel, low-alloyed	kg	672	Cable short
Steel, low-alloyed	kg	288	Cable long
Si, Glass backsheet module integration_CN_NSE5	kWp	104	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	104	See Table 19
Grid connection_Si system_NSE5	kWp	104	See Table 20
Steel, low-alloyed	kg	718.73	PV supporting frame 1
Steel, low-alloyed	kg	646.86	PV supporting frame 2
Steel, low-alloyed	kg	970.29	Walkway
Metal working, average for steel product manufacturing	kg	11532	Sum of mass of all steel components. Process modified by eliminating steel input. Geography, ‘Rest of the World’, production process

Table 12: Inventory for Module 2 for high above sea structure, Steel. The ecoinvent processes are taken from the cut-off database and are global market for processes.

Ecoinvent Process	unit	Amount	Comment
Output			
Module 2 - High above sea level_Steel	p	1	This is a "piece", i.e. a single module
Inputs			
Steel, low-alloyed	kg	990.25	Space frame connectors.
Steel, low-alloyed	kg	3833.23	Beam horizontal
Steel, low-alloyed	kg	798.59	Beam vertical
Steel, low-alloyed	kg	672	Cable short
Steel, low-alloyed	kg	288	Cable long
Si, Glass backsheet module integration_CN_NSE5	kWp	104	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	104	See Table 19
Grid connection_Si system_NSE5	kWp	104	See Table 20
Steel, low-alloyed	kg	718.73	PV supporting frame 1
Steel, low-alloyed	kg	649.86	PV supporting frame 2
Steel, low-alloyed	kg	970.29	Walkway
Metal working, average for steel product manufacturing	kg	7970	Sum of all Steel components. Process modified by removing the steel input.

Table 13: Inventory for the complete lifecycle of the Steel High above sea floating structure, for 1 kWp. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
High above sea level Steel complete structure	kWp	1	
Inputs			
Module 1 - High above sea level_Steel	p	0.0028	See Table 8
Module 2 - High above sea level_Steel	p	0.00673	See Table 9
Polyethylene, high density, granulate	kg	11.86	Mooring lines
Polyethylene, high density, granulate	kg	1.04	Buoys in mooring lines
Polyethylene, high density, granulate	kg	0.139	Signalling buoys
Extrusion, plastic pipes	kg	13	Extrusion of all materials above
Steel, low-alloyed	kg	10.4	Anchors
Metal working, average for steel product manufacturing	kg	10.4	Process modified by removing the steel input. Geography: Rest of the World, production process
Epoxy resin, liquid	kg	1.72	Steel coating assumed as 2% of steel mass. Geography: Europe
Fuel burned for maintenance	MJ	1250	
Fuel consumption for installation and decommissioning	MJ	1436	

2.3.4.3 Just above sea level – Aluminium

The following tables include the material and fuel use for the Just above sea floating structure in aluminium. Initially the amount to build a single module are presented and then the inventory for 1kWp structure is given in Table 15.

Table 14: Inventory for the Module for just above sea structure, Aluminium. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Single module just above sea level	p	1	This is a "piece", i.e. a single module
Inputs			
Polyethylene, high density, granulate	kg	194.4	Floaters
Extrusion, plastic pipes	kg	194	Floaters
Aluminium alloy, AlMg3	kg	105	Beam length
Aluminium alloy, AlMg3	kg	160.8	Beam width
Si, Glass backsheet module integration_CN_NSE5	kWp	8.64	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	8.64	See Table 19
Grid connection_Si system_NSE5	kWp	8.64	See Table 20
Aluminium alloy, AlMg3	kg	60	PV supporting frame 1
Aluminium alloy, AlMg3	kg	54	PV supporting frame 2
Aluminium alloy, AlMg3	kg	110	Walkway
Metal working, average for aluminium product manufacturing	kg	489.8	Sum of all al components. process modified removing the Al input. Geography: Rest of the World, production process

Table 15: Inventory for the complete lifecycle of the Aluminium Just above sea floating structure, for 1 kWp. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Just above sea level Steel complete structure	kWp	1	This is a "piece", i.e. a single module
Inputs			
Single module just above sea level	p	0.12	See Table 11
Polyethylene, high density, granulate	kg	11.86	Mooring lines
Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U	kg	1.04	Buoys in mooring lines
Polyethylene, high density, granulate	kg	0.14	Signalling buoys
Extrusion, plastic pipes	kg	13	Extrusion of plastic parts
Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U	kg	10.4	Walkway
Metal working, average for steel product manufacturing	kg	10.4	Metal working
Fuel consumption for installation and decommissioning	MJ	506	
Fuel burned for maintenance	MJ	1250	
Epoxy resin, liquid	kg	0.21	Steel coating, assumed as 2% of steel mass. Geography: Europe

2.3.4.4 Just above sea level - Steel

The following tables include the material and fuel use for the Just above sea floating structure in steel. Initially the amount to build a single module are presented and then the inventory for 1kWp structure is given in Table 17.

Table 16: Inventory for the Module for just above sea structure, Steel. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Single module just above sea level_steel	p	1	This is a "piece", i.e. a single module
Inputs			
Polyethylene, high density, granulate	kg	194.4	Floaters
Extrusion, plastic pipes	kg	194	Floaters
Steel, low-alloyed	kg	102.3	Beam length
Steel, low-alloyed	kg	156.7	Beam width
Si, Glass backsheet module integration_CN_NSE5	kWp	8.64	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	8.64	See Table 19
Grid connection_Si system_NSE5	kWp	8.64	See Table 20
Steel, low-alloyed	kg	58.5	PV supporting frame 1
Steel, low-alloyed	kg	52.6	PV supporting frame 2
Steel, low-alloyed	kg	107.2	Walkway
Metal working, average for steel product manufacturing	kg	477.3	Sum of all al components. process modified removing the Al input. Geography: Rest of the World, production process

Table 17: Inventory for the complete lifecycle of the Steel Just above sea floating structure, for 1 kWp. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Just above sea level Steel complete structure	kWp	1	
Inputs			
Single module just above sea level_steel	p	0.12	See Table 13
Polyethylene, high density, granulate	kg	11.86	Mooring lines
Polyethylene, high density, granulate	kg	1.04	Buoys in mooring lines
Polyethylene, high density, granulate	kg	0.14	Signalling buoys
Extrusion, plastic pipes	kg	13	Extrusion of plastic parts
Steel, low-alloyed	kg	10.4	Walkway
Metal working, average for steel product manufacturing	kg	10.4	Metal working. Process modified removing steel input. Geography: Rest of the World, production process
Fuel consumption for installation and decommissioning	MJ	506	Fuel consumption for installation and decommissioning
Fuel burned for maintenance	MJ	1	See separate inventory
Epoxy resin, liquid	kg	1.1	Steel coating, assumed as 2% of steel mass. Geography: Europe

2.3.4.5 Ring membrane structure

As in the previous cases, at first the inventory for 1 module (ring) is presented and then the inventory for 1 kWp of the structure is shown.

Table 18: Inventory for one ring module. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Ring membrane module	p	1	This is a "piece", i.e. a single module
Inputs			
Steel, low-alloyed	kg	57770	Ring
Metal working, average for steel product manufacturing	kg	57770	Ring. Process modified removing the steel input. Geography: Rest of the World, production process
Polybutadiene	kg	48129	Membrane
Textile, nonwoven polyester	kg	66888	Membrane reinforcement
Si, Glass backsheet module integration_CN_NSE5	kWp	1338	See Table 18
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	1338	See Table 19
Grid connection_Si system_NSE5	kWp	1338	See Table 20
Epoxy resin	kg	19	Glue to attach the panels to the membrane

Table 19: Inventory for the complete lifecycle of the Ring membrane structure, for 1 kWp. The ecoinvent processes are taken from the cut-off database and are global market for processes, unless indicated.

Ecoinvent Process	unit	Amount	Comment
Output			
Ring membrane structure	kWp	1	
Inputs			
Ring membrane module	p	0.0007	See Table 15
Polyethylene, high density, granulate	kg	15.048	Mooring lines
Polyethylene, high density, granulate	kg	1.32	Buoys on mooring lines
Polyethylene, high density, granulate	kg	0.176	Signalling buoys
Extrusion, plastic pipes	kg	16.5	
Steel, low-alloyed	kg	11	Anchor
Metal working, average for steel product manufacturing	kg	11	Anchor. Process modified removing the steel input. Geography: Rest of the World, production process
Fuel consumption for installation and decommissioning	MJ	658	
Fuel burned for maintenance	MJ	1250	
Epoxy resin, liquid	kg	1,06	Steel coating, 2% of steel mass. Geography: Europe

2.3.4.6 Updates to fuel consumption inventory

As in the previous calculations, the fuel consumption for all the vessels used in this study, has been modelled with the ecoinvent card “Diesel, burned in fishing vessel”.

Table 20: Updated fuel consumption for all structure types for installation, decommissioning and operation and maintenance.

	High above sea Aluminium	High above sea steel	Just above sea aluminium	Just above sea steel
Installation	896 MJ/kWp	896 MJ/kWp	680 MJ/kWp	680 MJ/kWp
O&M	348 MJ/kWp	348 MJ/kWp	348 MJ/kWp	348 MJ/kWp
Decommissioning	896 MJ/kWp	896 MJ/kWp	680 MJ/kWp	680 MJ/kWp

2.3.5 Inventory Tables - Silicon Photovoltaics

This section presents the inventory for the Silicon Photovoltaic (Si PV) panels, including the inverters and cabling. As the main focus of this report was on different structures and not the PV panels, these tables are shown in the Appendix A2. The inventory of the PV system has been divided into four parts: PV cell, panel manufacturing (i.e. the energy and material necessary to produce a panel from Si PV cells), installation (i.e. interconnection cables and

MC4 junction boxes) and inverter connection (i.e. inverter and cable). The inventory for the production of the PV solar cell (see Table 22) has been taken from (Müller et al. 2021). The inventory for the panel manufacturing (see Table 23) has been also based on (Müller et al. 2021), with the following modifications:

- Packaging and auxiliary materials (e.g. Pallets, factory, lubricants, etc) have been removed as out of scope for the present study.
- The materials related to the junction box (Glass fibre reinforced plastic) has been removed, as in this analysis the junction boxes have been modelled as part of installation.
- The adhesive material has been changed to “Polymethyl methacrylate, sheet {GLO}| market for polymethyl methacrylate, sheet | Cut-off, U” (indicated in Table 23 with an *) based on discussions with TNO PV experts.
- The inventory has been upscaled to 1 kWp from m2, based on the area necessary for the generation of 1 kWp, which is 4.5 m2.

The inventory for the MC4 connectors and junction boxes together, see Table 24, has been based on internal TNO knowledge, in close cooperation with the Solar Technology and Application group: the MC4 Junction box connectors were available in house and have been analysed to determine the material (Copper and PPE) in each MC4 junction box connector. It was assumed that each module contained 2 MC4 Junction box connectors and a cable connecting it to the next panel. The inverter was modelled with the 500 kW process card available in ecoinvent. It was assumed that for each solar farm of 15MW a series of 30 500kW inverters were used and that 10 m of cabling was necessary to connect the PV arrays to their relative inverter. These amounts were downscaled to 1 kWp and are reported in Table 25. In all cases, to model the cables the standard ecoinvent process card for copper cable has been used after being adapted for thinner cables (see details in inventory tables).

2.4 Impact Assessment

Impact assessment describes the phase, where the long list of interventions is translated into a number of so-called midpoint impact categories by modelling the underlying environmental mechanism. This step allows to add all interventions that contribute to the same environmental problem in one common unit. For the carbon footprint, emissions of greenhouse gases are re-calculated to kg CO2-equivalents (CO2-eq) by using Global Warming Potentials (GWP) that express the contribution of a gas to radiative forcing relative to that of CO2. More details on impact assessment levels and other impact categories have been given in previous NSE reports. In this report, the GWPs from the latest IPCC report were used (IPCC 2021 GWP 100a). The modelling was carried out with the commercial software SimaPro, values for the future sensitivity scenario where derived using open source software Activity Browser.

3 Results

3.1 First results

This section displays the first results obtained based on the data and assumptions explained in the previous sections. Figure 1 shows the breakdown of the carbon footprint per structure type, per 1 kWp. As it can be seen from Figure 1, the structures with aluminium frames have a higher carbon footprint than the structures based on steel elements. This is due to the larger carbon footprint of aluminium in comparison with the carbon footprint of steel.

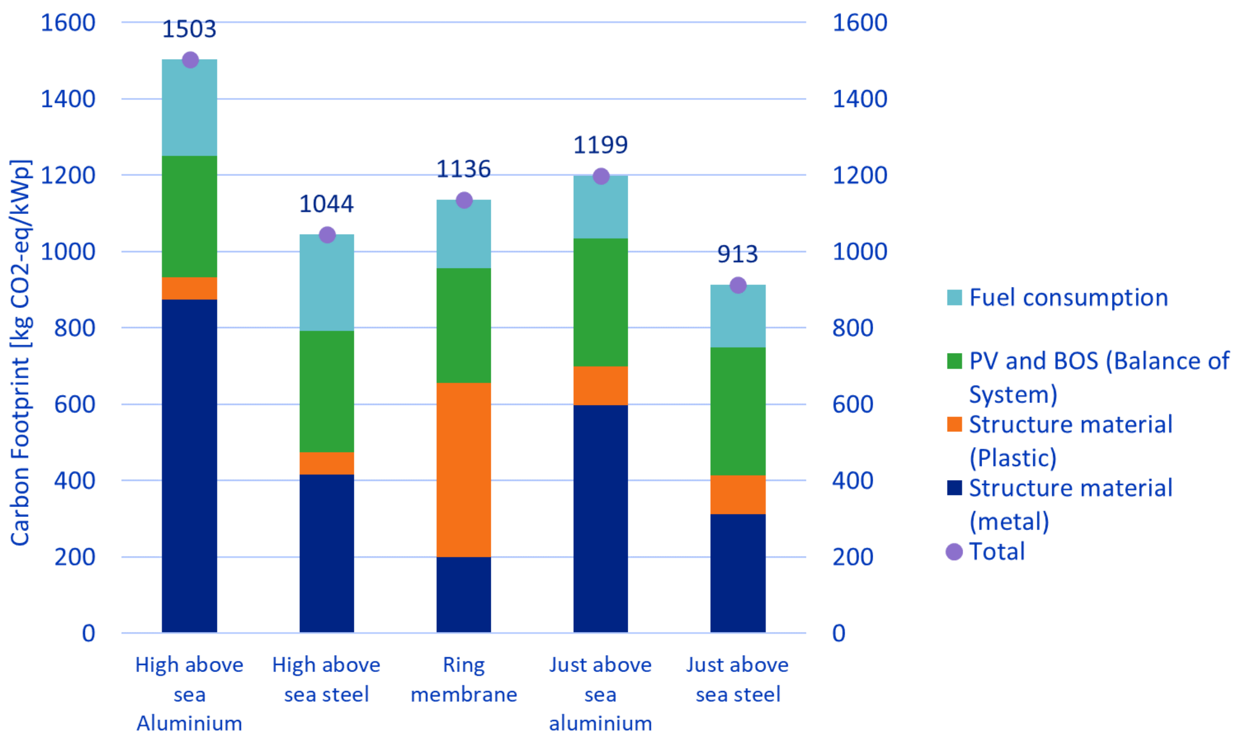

Figure 1: Breakdown of carbon footprint [kg CO2-eq/kWp] of all floating solar structures. The numbers on the bars indicate the total carbon footprint per structure type.

Below the most important contributors to carbon footprint per structure type and material choice are described in more detail:

- In the case of the aluminium high above sea structure, it can be seen that the largest contribution (58%) is given by the metals used in the structure. This is largely due to the aluminium used in the modules structure and a small amount of steel used for the anchors. The second largest contribution (21%) is given by the PV installation (PV panels and BOS) and then the fuel use (17%). Of this, the maintenance delivers the largest contribution (8%, not shown).

- In the case of the aluminium just above sea structure, it can be seen that the largest contribution (50%) is given by the metals used in the structure. This is largely aluminium and a small amount of steel used for the anchors. The second largest contribution (28%) is given by the PV installation (PV panels and BOS) and then the fuel use (14%). Also in this case, the maintenance delivers the largest contribution (10%).
- In the case of the ring membrane structure, the largest contribution (40%) is given by the plastic used in the structure: this is mostly due to the membrane, which is modelled as polybutadiene (contributing 12%) and nonwoven polyester textile (contributing 24%), and the HDPE floaters contributing the remaining 4%. The second largest contribution (27%) is given by the PV installation (PV panels and BOS) followed by the steel ring (18%) and the fuel use (16%).
- In the case of the steel high above sea structure, the largest contribution (40%) is given by the metals used in the structure. This is steel, mostly used in the module structure and a small amount for the anchors. The second largest contribution (31%) is given by the PV installation (PV panels and BOS) and then the fuel use (24%), of which the maintenance delivers the largest contribution (11%).
- In the case of the steel just above sea structure, largest contribution (37%) is given by the PV installation (PV panels and BOS). The second largest contribution (34%) is given by the steel used in the modules and the anchors. The third largest contribution (18%) is given by the fuel use (maintenance 13%).

3.2 Updates to results

This section displays the final results obtained after integrating the changes described in section 2.3.1.1 and 2.3.3.4. Figure 2 shows the updated breakdown of the carbon footprint [kg CO2-eq/kWp] of all floating solar structures. The results for the ring membrane have been shaded, as no updates have been made for this structure type, but were left in the figure for a clearer comparison with Figure 1.

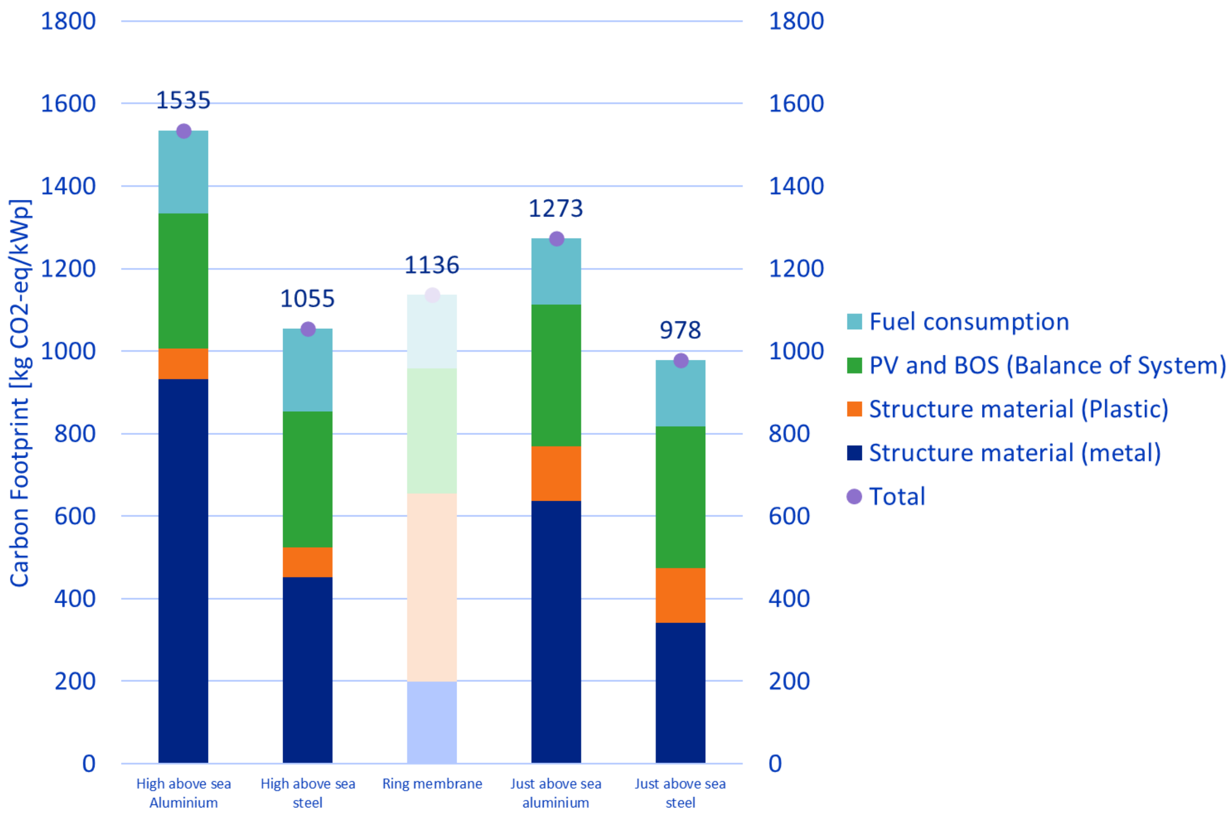

Figure 2: Updated breakdown of carbon footprint [kg CO2-eq/kWp] of all floating solar structures. The numbers on the bars indicate the total carbon footprint per structure type.

As it can be seen comparing the results displayed in Figure 1 and Figure 2, the updated fuel and material use did not lead to any major changes in the carbon footprint of the structures. Overall, there is a slight increase in the footprint of all structures. The fuel consumption, and associated carbon footprint, is reduced with the new calculations for all structures, but this reduction in carbon footprint is compensated (and slightly exceeded) by the higher carbon footprint associated with the metal working processes. The slight increment therefore can be attributed partially to the updated metal working process, but it is mostly associated with an increase of the carbon footprint of the plastic (HDPE) used in the floating structures. This increment can be explained by the use of a later ecoinvent database (see Section 2.3.1.1) Table 21 summarises the contribution breakdown of the carbon footprint of the different structures per material choice.

Table 21: Contribution breakdown to carbon footprint per structure type and material choice (Updated data)

	High above sea Aluminium	High above sea steel	Just above sea aluminium	Just above sea steel
Structure material (metal)	61%	43%	50%	35%
Structure material (Plastic)	5%	7%	10%	13%
PV and BOS (Balance of System)	21%	31%	27%	35%
Fuel consumption	13%	19%	13%	16%

3.3 Updates: Sensitivity on future energy mixes

This section displays the results obtained for the estimated future carbon footprint of the different floating solar structures in 2030 and 2050, based on the future carbon footprints of aluminium and steel, calculated as explained in section 2.3.2.

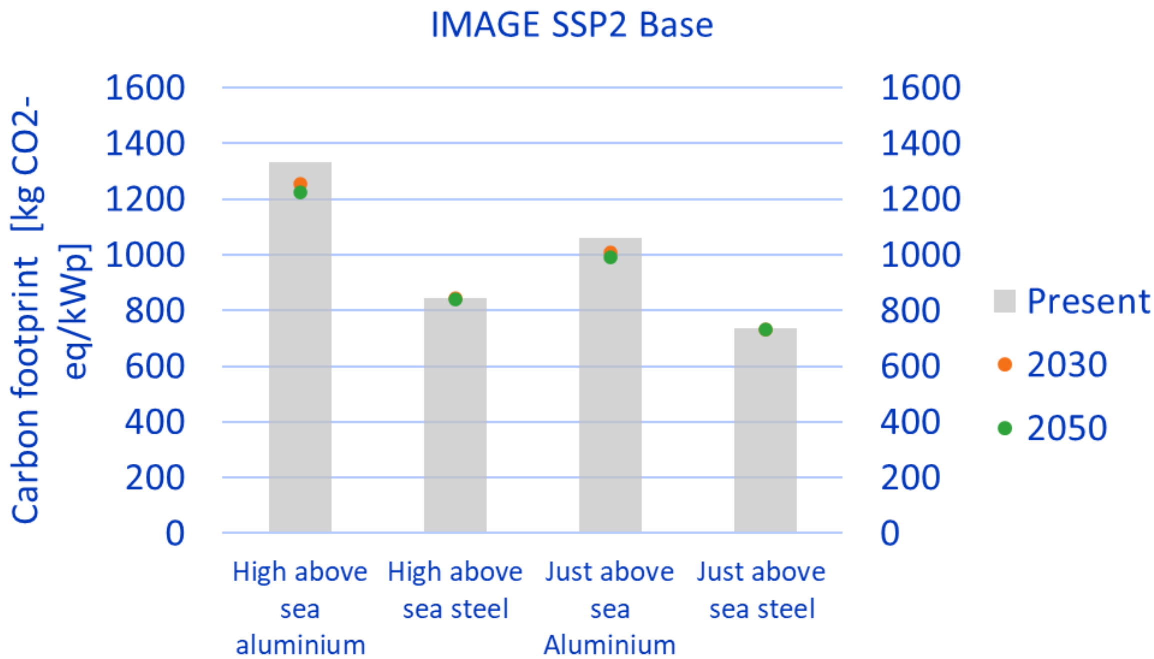

Figure 3: Carbon footprint of the different structures in 2030 and 2050, considering the future carbon footprint of steel and aluminium included in the IAM IMAGE SSP2 Base.

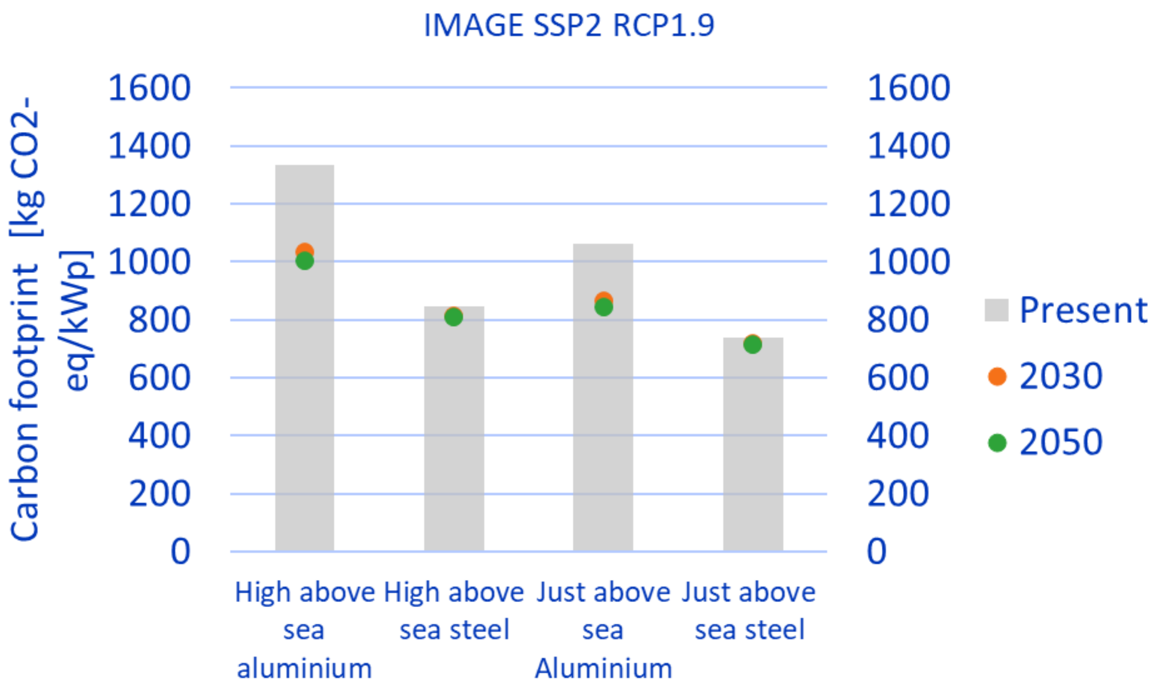

Figure 4: Carbon footprint of the different structures in 2030 and 2050, considering the future carbon footprint of steel and aluminium included in the IAM IMAGE SSP2 RCP 1.9

As it can be seen from Figure 3, without climate policy no significant differences in the carbon footprint of the structures was found. The results displayed in Figure 4 instead show a clear reduction in carbon footprint, especially in the case of the aluminium structures: -23% and -25% for the High above sea level structure in aluminium, -19% and -21% for the Just above sea level structure in aluminium for 2030 and 2050 respectively and -4% for the High above sea level structure in steel, 3% and -21% for the Just above sea level structure in steel for 2030 and 2050. Aluminium shows a larger reduction due to the higher use of electricity which becomes decarbonized easier than other energy sources.

4 Discussion and recommendations

Looking at the results presented in the previous section, it can be seen that in most cases the structural material (metals and plastics) delivers the largest contribution to the carbon footprint, followed by the PV installation and fuel use. As already mentioned, the impact of aluminium structures is considerably higher than the impact of steel structures, even though a large recycled portion was assumed in the analyses (70%). This is largely due to the larger carbon footprint of aluminium with respect to steel. This, in turn, is caused by the electricity consumption necessary for the aluminium production process. The impact of the ring membrane structure is in between the aluminium structures and the steel structures. For the same metal type, the high above sea level structures have a higher impact than the just above sea level structures due to higher material use. Steel high above sea level structures still have lower footprint than aluminium just above sea level and membrane structures.

From these preliminary results, it can be concluded that the choice of the material has a high influence of the carbon footprint. The carbon footprint can be potentially reduced by including more recycled material. As shown in the previous NSE4 project (Hauck, De Simon, and Snoek 2022), the origin of the steel (primary vs secondary) reduced the carbon footprint and a similar observation can be expected for Aluminium, even though here already a large proportion of secondary material is considered. The impacts of the PV panels on the structure are also considerable, especially in the steel structures. In this case, silicon PV panels were chosen as the most commonly available on the market, but thin film PV technologies are expected to have a smaller environmental impact with respect to Si PV (Maalouf et al. 2023). Therefore, choosing another PV technology could also support in reducing the carbon footprint. Designing for decommissioning and maximizing recyclability of materials and components can contribute to enhancing circularity and likely the carbon footprint. Fuel use for maintenance had a minor, but non-negligible contribution to carbon footprint. NSE 4 showed that replacing MDO for green or blue Hydrogen, for example in a dual-fuel engine, could also reduce the carbon footprint further.

The present results offer a good benchmark and insight on the carbon footprint of different floating solar structures but have to be considered preliminary results as, at the time of writing, little information is known on the differences that could arise during the electricity generation phase between the floating solar platforms. Therefore, they all have been modelled equally. If evidence of different production or maintenance requirements from different floating systems would arise, a separate sensitivity analysis will be carried out. A list of possible differences to investigate in a future sensitivity analysis is given here.

- Lifetime: it could be possible that different structures have a different lifetime due to the different materials employed especially in the case of the ring membrane platform this is not sure. Repairs and maintenance of the platform itself (e.g. substitution of parts or modules) have also not been taken into account at the moment, which could give rise to significant differences in the carbon footprint of the structures.
- Maintenance: The fuel use from maintenance contributed substantially to the carbon footprint of the floating solar structures. However, it is possible that different structures have different cleaning needs, or for example, coating maintenance for the steel structure.
- The electricity production of the floating solar structures has been excluded from the system boundaries of this study, as based on the current information, no differences in electricity generation are expected from the structures. As in the case of the maintenance, it would be interesting to investigate the effect of the different structure construction on the electricity generation during the lifetime of the solar platforms.

All structures have been modelled based on a projection of future mass produced offshore floating structures with the current state of knowledge, using generalised non-optimised designs. However, metal production, electricity generation (i.e. the sources used for the country electricity mix), solar panel performance and fuel use for transportation might change in the future. This is explored in the next section.

4.1 Discussion - Updated results

To further validate the results with across the offshore floating solar sector as it is in 2024, interviews with technology developers designing such devices were held. From the interviews conducted with the companies and technology developers no other significant differences emerged with respect to material use and fuel consumption for installation and decommissioning, and the input data used for this model has been essentially validated. As already mentioned in section 3.3, the updated fuel use and metal working process did not lead to significant changes in the carbon footprint of the floating structures. In discussions carried out with Onepeterson, it emerged that potential maintenance differences could arise between steel and aluminium structures due to the necessity of coating maintenance in the case of steel structures. Unfortunately, these differences could not be quantified in time for the submission of this report. As has been mentioned on discussions within NSE 5, for all structures, cleaning requirements could potentially increase with temperature rise. More insights into these developments as well as differences between fresh and salt water would support the development of floating PV. Similarly, it could be interesting to look at the employment of electric vessels for maintenance purposes.

The changes in the future carbon footprint of the aluminium structures depicted in Figure 4, are mostly due to the expected reduction of the carbon footprint of the electricity mix. This is particularly relevant for aluminium due to the large electricity amounts consumed in the aluminium production process.

5 References

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Appendix A: Solar farm structures design

A.1 Module disposition and design

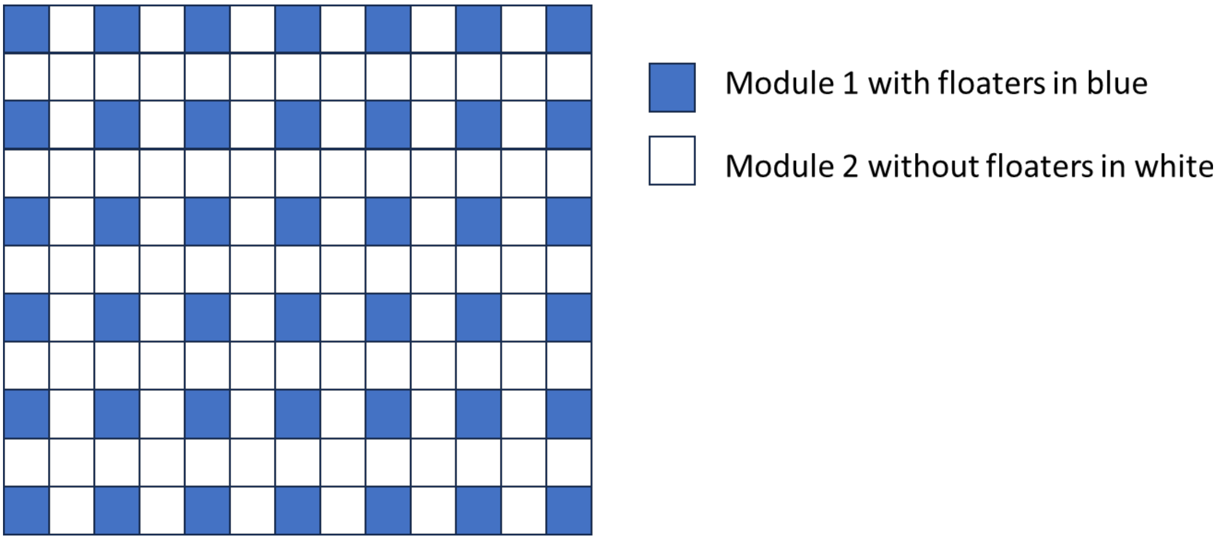

Figure 5: Module 1 (42 modules) and module 2 (101 modules) disposition for high above sea structure. The modules 2 type are supported by Modules 1. Note: The modules 1 on the edges seem to carry less weight, but they also support the mooring system and might have to carry extra mass to prevent uplifting during storms

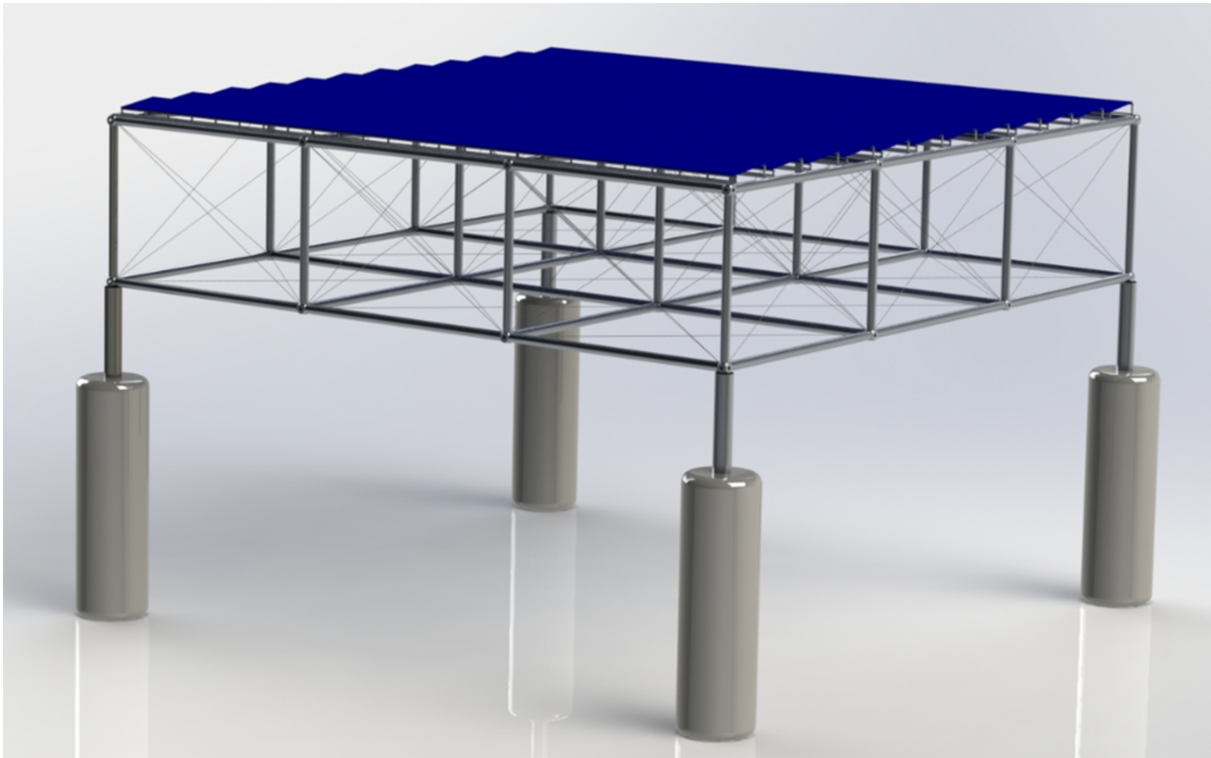

Figure 6: High above sea level module structure (DEME design, Module type 1 with floaters)

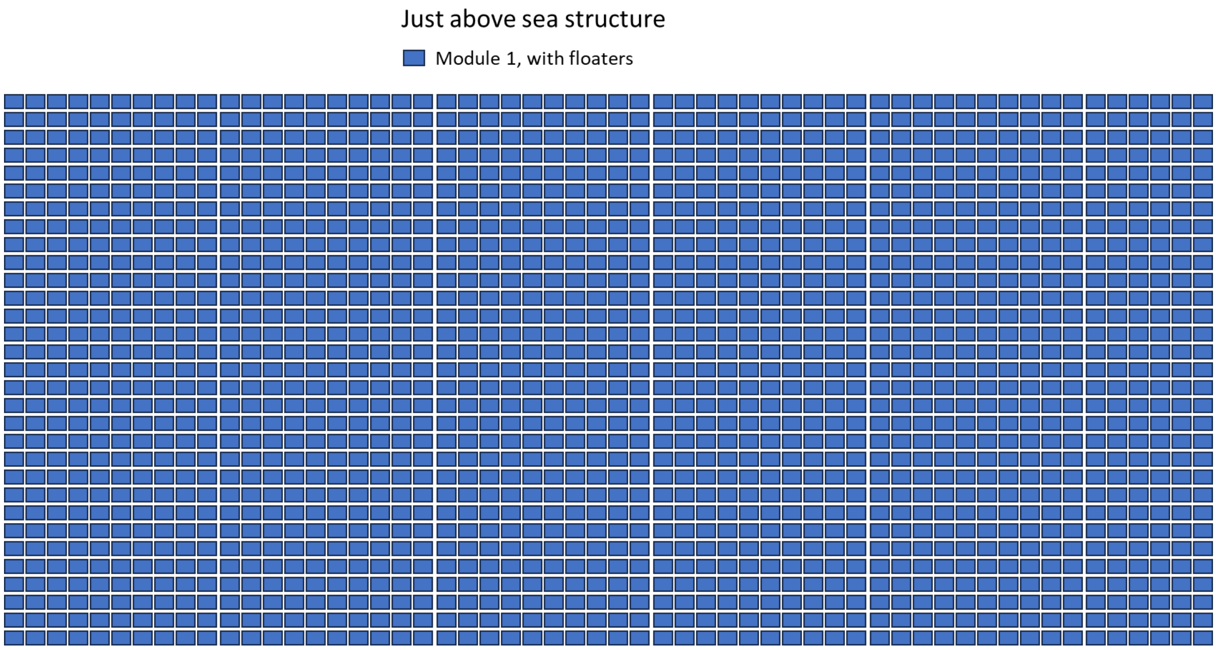

Figure 7: Module disposition for just above sea structure

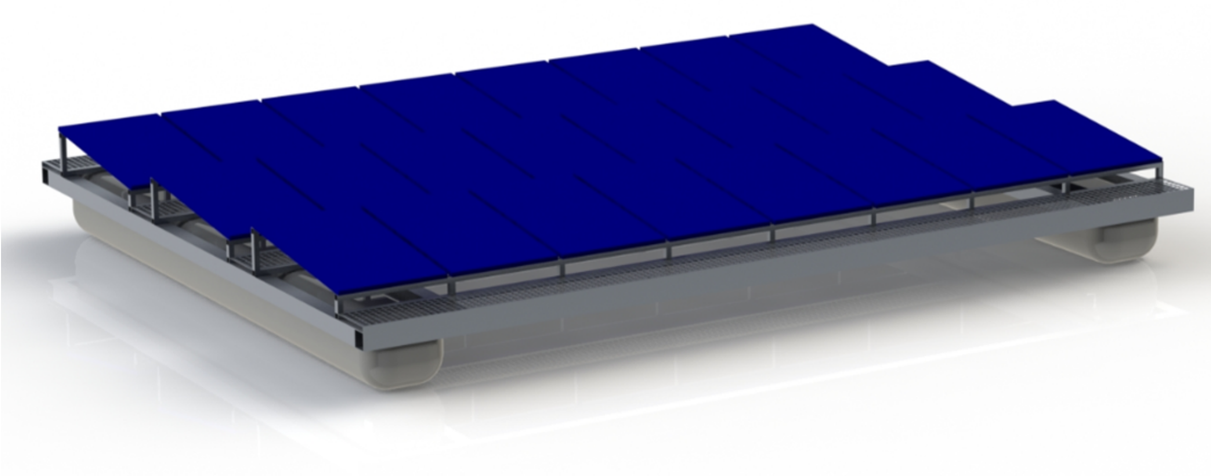

Figure 8: Just above sea level module structure (DMEC design)

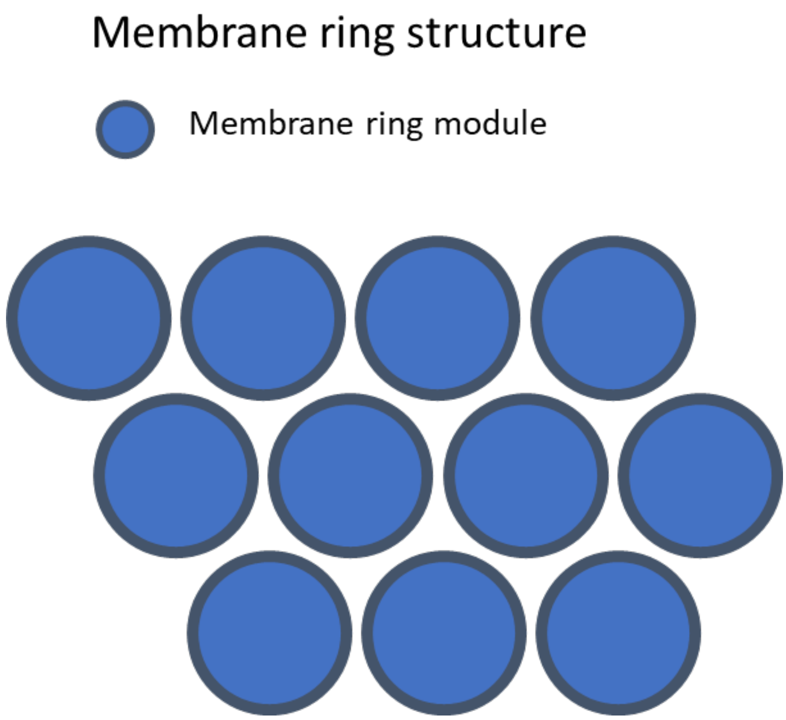

Figure 9: Hypothetical example of module disposition for membrane ring structure

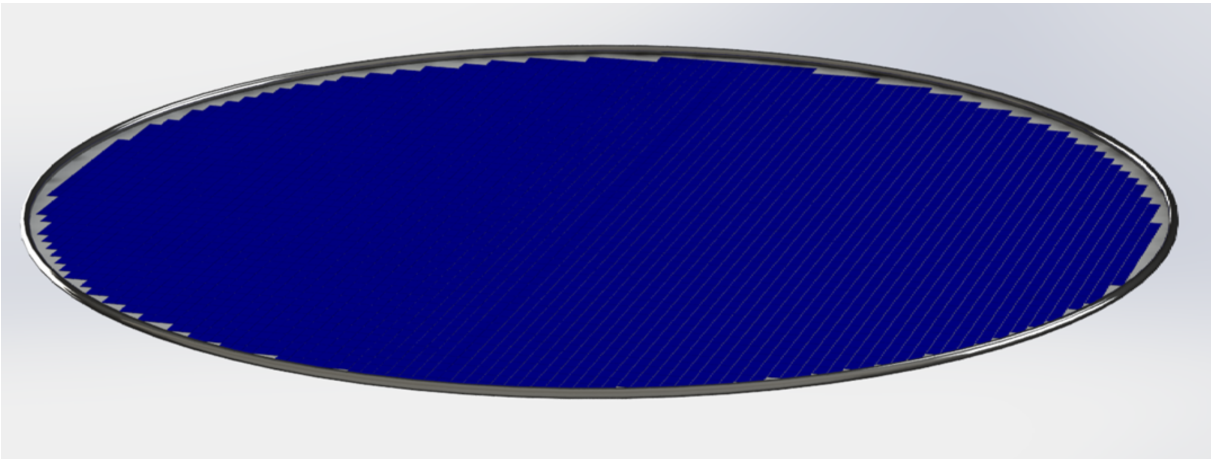
Figure 10: Ring membrane module structure (DMEC design)

A.2 Inventory tables of PV panels and installation

Table 22: Inventory for the PERC cell production, based on (Müller et al. 2021)

Ecoinvent Process	unit	Amount	Comment
Output			
Si, PV cell, PERC half cell production, Glass backsheet module_CN_NSE5	kWp	1	
Inputs			
170 µm mono M6 bricking and wafer production, photovoltaic_CN	m2	4.63	
TMAI purification_CN	kg	0.00131	
Ammonia, anhydrous, liquid {RoW}| market for ammonia, anhydrous, liquid | Cut-off, U	kg	0.0749	
Calcium chloride {RoW}| market for calcium chloride | Cut-off, U	kg	0.94	
Hydrochloric acid, without water, in 30% solution state {RER}| market for hydrochloric acid, without water, in 30% solution state | Cut-off, U	kg	0.309	
Hydrogen fluoride {RER}| market for hydrogen fluoride | Cut-off, U	kg	0.339	
Hydrogen peroxide, without water, in 50% solution state {RER}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, U	kg	0.427	
Metallization paste, back side {RER}| market for metallization paste, back side | Cut-off, U	kg	0.00463	
Metallization paste, back side, aluminium {RER}| market for metallization paste, back side, aluminium | Cut-off, U	kg	0.0409	
Metallization paste, front side {RER}| market for metallization paste, front side | Cut-off, U	kg	0.0158	
Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state | Cut-off, U	kg	0.373	
Nitrogen, liquid {RER}| market for nitrogen, liquid | Cut-off, U	kg	11.9	
Nitrous oxide {GLO}| market for nitrous oxide | Cut-off, U	kg	0.0348	
Oxygen, liquid {RER}| market for oxygen, liquid | Cut-off, U	kg	1.52	
Phosphorus oxychloride {RER}| market for phosphorus oxychloride | Cut-off, U	kg	0.000826	
Photovoltaic cell factory {GLO}| market for photovoltaic cell factory | Cut-off, U	p	0	Deleted as auxiliary

Potassium hydroxide {GLO}| market for potassium hydroxide | Cut-off, U	kg	0.686	
Propane {GLO}| market for propane | Cut-off, U	kg	0.188	
Silicon tetrahydride {GLO}| market for silicon tetrahydride | Cut-off, U	kg	0.0128	
Solvent, organic {GLO}| market for solvent, organic | Cut-off, U	kg	0.0558	
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	kg	0.0935	
Water, completely softened {RoW}| market for water, completely softened | Cut-off, U	kg	105	
Water, deionised {RoW}| market for water, deionised | Cut-off, U	kg	179	
Electricity/heat			
Electricity, medium voltage {CN}| market for | Cut-off, U	kWh	27.4	
Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100kW | Cut-off, U	MJ	16.1	
170 µm mono M6 bricking and wafer production, photovoltaic_CN	m2	4.63	
Emissions to air			
Aluminium	kg	0.00351	
Ethane, hexafluoro-, HFC-116	kg	0.000538	
Hydrochloric acid	kg	0.00121	
Hydrogen fluoride	kg	2.20E-05	
Lead (II)	kg	1.58E-06	
Methane, tetrafluoro-, CFC-14	kg	0.00112	
Nitrogen oxides	kg	0.000227	
NMVOC, non-methane volatile organic compounds	kg	0.879	
Particulates, < 2.5 um	kg	0.0121	
Silicon	kg	0.00033	
Water/m3	m3	0.0763	
Emissions to water			
Water/m3	m3	1.26	
Waste to treatment			
Waste, from silicon wafer production, inorganic {GLO}| market for waste, from silicon wafer production, inorganic | Cut-off, U	kg	0.0291	
Wastewater from PV cell production {GLO}| market for wastewater from PV cell production | Cut-off, U	m3	0.0599	

Table 23: Inventory for the panel manufacturing based on (Müller et al. 2021) with the modifications carried out for this study

Ecoinvent Process	unit	Amount	Comment
Output			The comment section provides an educated guess (and where possible a reference) for the expected function of the material in the PV panel
Si, Glass backsheet module integration_CN_NSE5	kWp	1	
Inputs			
EUR-flat pallet {RER}| EUR-flat pallet production | Cut-off, U	p	0	Deleted as part of the packaging
PERC half cell production, mono Si M6 wafer_CN	m2	0.898	PV cell
Aluminium alloy, AlMg3 production_CN	kg	7.63	Frame (Jungbluth et al. 2012)
Flat glass production, uncoated _CN	kg	40.4	Front glass
1-propanol {GLO}| market for 1-propanol | Cut-off, U	kg	0.0869	Soldering flux (Jungbluth et al. 2012)
Adipic acid {GLO}| market for adipic acid | Cut-off, U	kg	0.00186	cleaning fluid
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	kg	0.748	Copper ribbon for cell interconnection
Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	kg	0	Deleted as part of the packaging
Diode, auxilliaries and energy use {GLO}| market for diode, auxilliaries and energy use | Cut-off, U	kg	0.0142	Diode
Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	kg	4.01	Encapsulant
Extrusion, plastic film {GLO}| market for extrusion, plastic film | Cut-off, U	kg	1.7	Backsheet
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, U	kg	0	Junction box. Deleted (Jungbluth et al. 2012)
Lead {GLO}| market for lead | Cut-off, U	kg	0.0546	Stringing (de Wild-Scholten et al. 2019)
Lubricating oil {RER}| market for lubricating oil | Cut-off, U	kg	0	auxiliary materials. Deleted
Packaging film, low density polyethylene {GLO}| market for packaging film, low density polyethylene | Cut-off, U	kg	0	Packaging. Deleted

Photovoltaic panel factory {GLO}| market for photovoltaic panel factory | Cut-off, U	p	0	Deleted
Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U	kg	1.42	Backsheet (Jungbluth et al. 2012)
Polybutadiene {RER}| polybutadiene production | Cut-off, U	kg	0.122	Edge sealant proxy (supposition).
Polyethylene, low density, granulate {GLO}| market for polyethylene, low density, granulate | Cut-off, U	kg	0.277	Backsheet
Polyvinylfluoride, film {GLO}| market for polyvinylfluoride, film | Cut-off, U	kg	0.228	Backsheet (Jungbluth et al. 2012)
Polymethyl methacrylate, sheet {GLO}| market for polymethyl methacrylate, sheet | Cut-off, U	kg	0.845	kit to attach frame and junction box and for diaphragm of laminator (Jungbluth et al. 2012). Substituted with Polymethyl methacrylate, sheet {GLO}| market for | Cut-off, U
Tempering, flat glass {GLO}| market for tempering, flat glass | Cut-off, U	kg	40.4	Front glass (Jungbluth et al. 2012)
Tin {GLO}| market for tin | Cut-off, U	kg	0.0525	String ribbon for intercel connection (de Wild-Scholten et al. 2019)
Wire drawing, copper {RER}| wire drawing, copper | Cut-off, U	kg	0.748	String ribbon for intercel connection (de Wild-Scholten et al. 2019)
Electricity/heat			
Electricity, medium voltage {CN}| market group for electricity, medium voltage | Cut-off, U	kWh	16.8	
Emissions to air			
Carbon dioxide, fossil	kg	0.11	
Heat, waste	MJ	67.7	
NMVOC, non-methane volatile organic compounds, CN	kg	0.0407	
Water/m3	m3	0.141	
Waste to treatment			
Waste mineral oil {RoW}| market for waste mineral oil | Cut-off, U	kg	0.00813	
Waste plastic, mixture {RoW}| market for waste plastic, mixture | Cut-off, U	kg	0.125	
Waste polyvinylfluoride {RoW}| market for waste polyvinylfluoride | Cut-off, U	kg	0.00456	
Municipal solid waste {RER}| market group for municipal solid waste | Cut-off, U	kg	0.49	

Table 24: Inventory for the Installation part (i.e. MC4 JB connectors and panel interconnecting cables)

Ecoinvent Process	unit	Amount	Comment
Output			
Si, Installation, Glass_Backsheet, industrial _EU_NSE5	kWp	1	
Inputs			
Polycarbonate {GLO}| market for polycarbonate | Cut-off, U	kg	0.135	2 MC 4 JB connectors (Proxy for PPE) per module.
Copper, anode {GLO}| market for copper, anode | Cut-off, U	kg	0.0432	Copper included in the MC 4 connectors. Two electrical contacts per MC4 connector (4g each). 2 MC4 connectors per each panel
Cable, three-conductor cable {GLO}| market for cable, three-conductor cable | Cut-off, U	m	0.193	Shielded copper cable (weight adjusted 60g/m vs 1,04 kg/m). One cable of 124 cm per panel.

Table 25: Inventory for the Inverter and cabling to the inverter

Ecoinvent Process	unit	Amount	Comment
Output			
Grid connection_Si system_NSE5	kWp	1	
Inputs			
Cable, three-conductor cable {GLO}| market for cable, three-conductor cable | Cut-off, U	m	0.00115	assume 10m for every inverter. Shielded copper cable (weight adjusted 60g/m vs 1,04 kg/m).
Inverter, 500kW {GLO}| market for inverter, 500kW | Cut-off, U	p	0.002	Assumed inverters of 500 kW, i.e. 30 inverters for 15 MW plant

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