3-1-2022

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Preprint: Hayibo, K.S., Mayville, P., Pearce, J., 2022. The Greenest Solar Power? Life Cycle Assessment of Foam-Based Flexible Floatovoltaics. *Sustainable Energy & Fuels*, 2022, 6, 1398 - 1413.
https://doi.org/10.1039/D1SE01823J

The Greenest Solar Power? Life Cycle Assessment of Foam-Based Flexible Floatovoltaics

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This study presents a life cycle analysis (LCA) of a 10-MW foam-based **floatovoltaics** (FPV) plant installed on Lake Mead, Nevada, U.S. A material inventory of the flexible crystalline silicon (c-Si)-based module involved massing and determination of material composition of the module's encapsulation layers with ATR/FTR spectroscopy and electron microscopy. The LCA was performed using SimaPro and the results were interpreted in terms of cumulative energy demands, energy payback time, global warming potential, GHG emissions, and water footprint including negative values for reduced evaporation. A sensitivity analysis was performed on the lifetime of the modules and the foam-based racking. The results show 30-year lifetime foam-based FPV system have one of the lowest energy payback times (1.3 years) and the lowest GHG emissions to energy ratio (11 kg CO_2 eq/MWh) in c-Si solar PV technologies reported to date. In addition, the foam-based FPV system also had 5 times less water footprint (21.5 m^3/MWh) as compared to a conventional pontoon-based FPV (110 m^3/MWh). The lifetime of the foam-based racking does not affect the result, while the lifetime of the modules has a significant effect on the lifecycle impacts of the foam-based FPV plant. Foam-based FPV has a net positive impact on the environment for CO_2 emissions and energy consumption if its lifetime is above 7.4 years and the technology has the potential to become the greenest c-Si-based solar PV technology if the lifetime of the modules can be guaranteed for at least 26.6 years. Future work is needed to determine these lifetimes of these systems and expand them.

Broader Context

Sustainable solar photovoltaic (PV) technology can further improve its environmental performance by reducing materials needed for systems providing a given amount of energy or providing other services. Recent work has shown floatovoltaics (FPV) to be promising candidates for greener PV because of their symbiotic relationship with water. A new type of FPV that uses only foam as the racking material was shown in this life cycle analysis study to be the greenest form of crystalline silicon (c-Si)-based PV to date if its lifetime reaches 30 years. This is because it has one of the lowest energy payback times (1.3 years) and the lowest GHG emissions to energy ratio (11 kg CO_2 eq/MWh) of any c-Si PV technology. In addition, FPV saves water from evaporating which could be critical in arid and semi-arid regions. The foam-based FPV system also has 5 times less water footprint (21.5 m3/MWh) as compared to even the water resource benefits of a conventional pontoon-based FPV (110 m^3/MWh). Overall, foam-based FPV has a net positive impact on the environment for CO_2 emissions and energy consumption if its lifetime is above 7.4 years but future work is needed to determine the lifetimes of different components of these systems and optimize them to maximize the environmental benefit.

Introduction

Converting solar energy directly to electricity with photovoltaic (PV) technology is well-established as a green sustainable solution to humanity's energy needs [1]. This has been determined by extensive life cycle analysis also known as life cycle assessment (LCA) studies, which have been historically primarily focused on land-based ground or roof-mounted PV systems. LCA studies vary in terms of the system boundary, the impact assessment methods as well as the study location. The lifecycle impacts of PV systems vary rapidly with time because of the continuous improvement in device performance, manufacturing methods and material types [2]. For example, a study conducted by Kreith et al. in 1990 investigated the energy use and the greenhouse gases (GHG) emissions of a ground mounted single crystalline (c-Si) PV system with a module efficiency of 8.5% in the United States (U.S.) for a lifetime of 30 years. The cumulative energy demand (CED) and the GHG emissions were estimated to 6,300 kWh/m² and 280 kg CO_2 eq/MWh, respectively [3]. In 2012, another study by Fthenakis et al. was conducted in the U. S. using the same lifetime (30 years), and mounting system (ground-mounted) as Kreith et al., with substantially improved modules efficiency (20.1%). According to Fthenakis et al., the system's CED was 1,295 kWh/m² and the GHG emissions was estimated to 64.2 kg CO_2 eq/MWh [4]. This shows a respective reduction of 79% and 77% in the energy use impact and GHG emissions impacts in 22 years due to technology improvement. In the time separating these two studies, other studies have examined the LCA of both c-Si and multi-crystalline (mc-Si) solar PV systems. Between 1990 and 2000, the life cycle analysis of first-generation solar PV systems resulted in GHG emissions values ranging from 50 kg Co_2 eq/MWh [5,6] to 280 kg CO_2 eq/MWh [3,7] for c-Si technologies, and 20 kg CO_2 eq/MWh [6,8] to 200 CO_2 eq/MWh [7,9] for multi-crystalline systems. During the same period, studies found that the energy payback time (EPBT) for c-Si PV systems were comprised between 2.5 years [5–7] and 15.5 years [6,8]; and was in the range of 1.7 years [6,7,10] to 3.2 years [5–7,10] for mc-Si technologies. During the following decade, with advances in life cycle analysis methodologies and availability of solar PV technologies inventories due to PV becoming a mainstream energy generation technology, more detailed and elaborated LCA were conducted on solar PV systems [11,12]. Studies conducted from 2001 to 2010 have evaluated the GHG emissions of single crystalline PV systems between 29 kg CO_2 eq/MWh [6,7,13] and 671 kg CO_2 eq/MWh [6,7,14] while multi-crystalline had emissions of 12 kg CO_2 eq/MWh [6,7,15] to 80 kg CO_2 eq/MWh [7,16]. In terms of energy consumption, the EBPT during the same period was 1.75 years [6,7,13] to 8 years [6] for c-Si systems while mc-Si PV systems had an energy payback time between 0.8 years [7,17] and 7.5 years [7,18]. The last decade (from 2010 to 2020) has seen a plethora of LCAs performed [11]. For example, the GHG emissions for both c-Si and mc-Si PV systems were estimated as low as 12 kg CO_2 eq/MWh [7,19–21], and the highest value were 67 kg CO_2 eq/MWh [22] and 88.7 kg CO_2 eq/MWh [7,23] for c-Si and mc-Si PV systems, respectively. On the other hand, the EPBT in that period was between 0.91 years [7,19] and 4.65 years [6,7,21,24] for c-Si, and mc-Si PV systems had an energy payback time ranged from 1.01 years [7,21,25] to 6.05 years [26]. It should be noted that amorphous silicon-based (a-Si:H) PV has even superior environmental performance, but has not gained market share because of lower efficiencies than c-Si and mc-Si that demands higher costs in the balance of systems [27,28].

In order to keep global temperatures on the planet from increasing over 2°C from preindustrial levels it is crucial to transition towards renewable and sustainable energy sources [29] since coal and other fossil-fuel-based energy sources are known to worsen climate change that is at the core of global temperatures rise [30,31]. One such energy source is solar PV that has become widely spread, accessible and has the potential to meet worldwide energy use by scaling [1,32]. Although better than coal technologies in terms of land occupancy when carbon emissions mitigation is considered [30], PV itself demands large surface areas to power society. This may cause a land use conflict with feeding an increasing world population. One method growing in popularity to alleviate land use conflicts is floating photovoltaics (or floatovoltaics (FPV)). FPV is not only deployed on un-used surface areas, but it also enjoys two primary synergies. First, water cools the PV increasing their power conversion efficiency [33–41] and second, the FPV reduces water evaporation, which can be extremely valuable in semi-arid and arid regions [38,42–44]. There are already some indications that FPV is environmentally superior to conventional land-based PV [45,46]. One method of improving environmental performance is to simply use less materials. This is observed in the PV field, where for example, frameless PV modules outperform framed modules in LCA studies [25,47]. The only study found in the literature that investigated the LCA of a conventional pontoon-based FPV has shown a high return on financial investment as compared to other PV systems [46].

A new type of FPV has been developed that uses foam racking and completely eliminates the need for the conventional racking infrastructure in pontoon-based FPV [41,48]. This has already been shown to be economically advantageous as with conventional land-based PV systems, the racking material makes up 8% of the total system cost for utility scale PV in the U.S. [49,50] and a far higher percentage for smaller PV systems. Furthermore, racking in conventional ground-mounted PV represents 8 to 23% of the total environmental impacts [15,51]. This offers the possibility that foam-based FPV are the greenest potential source of solar PV electricity. The environmental impacts of the newly-developed foam-based FPV system is not known, so this study aims to determine the environmental impacts and to explore the possibility of foam-based FPV becoming the greenest PV system to date. Specifically, this study will use a cradle to grave LCA on a 10-MW foam-based solar FPV plant located on Lake Mead, Nevada, U.S. Detailed technical analysis including both spectroscopy for material identification and electron microscopy for material volumes were conducted on the flexible PV modules to determine the overall material makeup. Then, energy payback time, carbon dioxide (CO_2) payback time, and a detailed water footprint using the water scarcity indicator (WSI) method, were calculated for the 10-MW foam-based FPV plant. A sensitivity of the lifetime of foam-backed FPV is run as the technology is newer than the expected lifetimes. The results are compared to prior LCAs for other PV technologies and discussed in the context of the overall environmentally superior technology. Finally, guidance is provided for improving the environmental performance further.

Material and Methods

Life Cycle Analysis

Life cycle assessment (LCA) is a scientific tool that is used to evaluate the environmental impact of a product system throughout the entirety of its lifecycle [24,52]. The lifecycle of a product system is made of several steps including the extraction of raw material, the manufacture stage, the use stage, the disposal or end-of-life stage of the product system, and all transportation that are needed between the different stages. An analysis that covers the entirety of the lifecycle of a product is called a cradle-to-grave analysis [52]. The LCA framework used in this study follows international LCA standards ISO 14040 and ISO 14044. According to these standards, an LCA study need to include a definition of the goal and scope, an inventory analysis, and an impact assessment and interpretation [52,53]. SimaPro 9 [54,55] has been used to execute the LCA simulation in this study.

Goal and Scope

In the present study, an LCA is performed on the after-market assembled foam-based FPV module that was proposed by Mayville et al. [41,48]. The flexible PV with mounting holes is specifically intended for marine applications and eliminates the need for a nylon tarp-based material to connect one module to another as was the case in the original study. The cradle-to-grave LCA covers the complete life cycle of the modules, the floating racking (foam, adhesive, and zip-ties), the inverters and the electrical installation. The life cycle stages that are

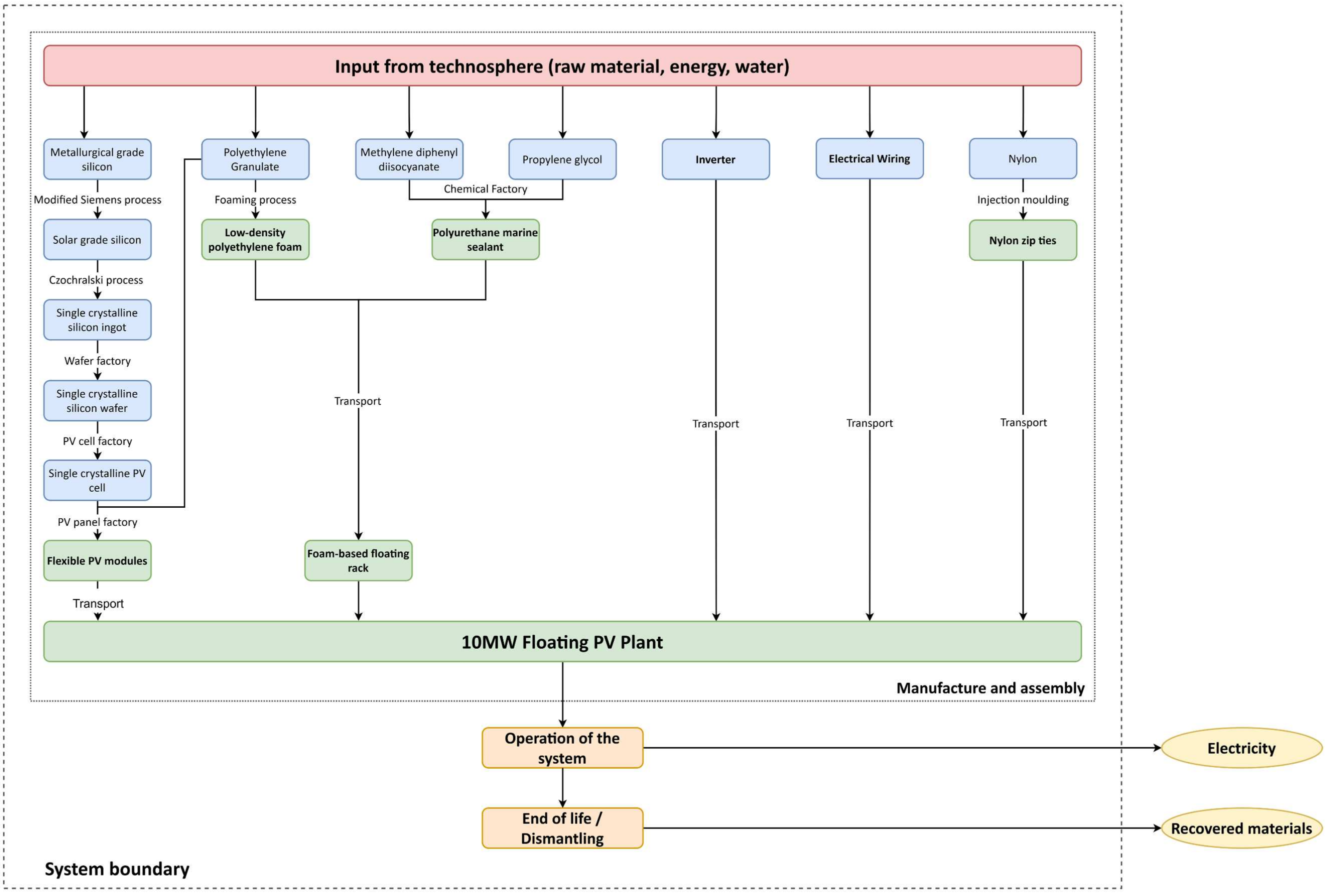

Figure 1. System boundary diagram of the foam-based FPV plant.

investigated are: the manufacture stage, the use stage, as well as the end-of-life stage.

The functional unit was chosen as 650.3 GWh delivered to the grid. This correspond to the amount of energy generated by a 10-MW solar FPV plant, with a 30-year lifetime operation, using foam-backed flexible SunPower [56] solar PV modules that are installed on the surface of Lake Mead, Nevada in the United States. This functional unit is obtained using an open-source energy production calculation sheet of a foam-based FPV developed in a recent study [41]. The model uses an empirical temperature model that is tailored to foam-based FPV modules, and accounts for losses as well as the degradation rate of the modules.

The system boundary in this study begins with the extraction of raw material for the manufacture of the flexible modules, the floating system, the inverters, and the cables for the electrical installation. The analysis also covers the operation of the plant and ends with the disposal of the equipment at the end of service life. The lifetime of the module used for the LCA is 30 years. According to the Solar Energy Industry Association (SEIA), a solar module's lifetime ranges from 20 to 30 years [57], and according to the flexible module's manufacturer, the modules can perform up to 40 years [58] (although it should be noted that the warranty for the flexible modules sold for marine applications is only 5 years [56]). The system boundary starts with the raw material extraction. The assessment covers the manufacture and assembly of the plant's equipment, the operation of the plant, and the decommissioning at the end-of-life. The system boundary ends when the energy is transferred to the electricity grid as shown on Figure 1.

Parameters	Value
Power Rating of the Plant	10 MW [59]
Installation Location	Lake Mead
Module Make and Model	SunPower SPR-E-Flex-110 [56]
Module STC Power	110 W [56]
Number of Modules	90,910 [59]
Module Degradation Rate	0.50% [60,61]
Average PV Efficiency Year 1	20.90% [59]
Average Annual Energy Production	21.7 GWh/year [59]
Lifetime of the System	30 years* [57]
Lifetime energy Production	650.3 GWh [59]
Projected Yearly Water Savings	115,000 m^3 [59]
Projected Lifetime Water Savings	3.4 million of m^3 [59]

Table 1. Design parameters of a 10-MW foam-based solar floatovoltaic plant located on Lake Mead, Nevada, United States.

* A sensitivity is run on the lifetime of FPV from 5-30 yrs in 5-yr spans

After the environmental impacts of the 10-MW foam-based FPV plant have been studied, and quantified on a per MWh basis, it is compared to a conventional pontoon-based FPV analyzed by Cromratie Clemons et al. [46]. The pontoon-based FPV components are the modules, the mounting structures, the pontoon floating system, the anchors, the connection cables and the inverters [46]. Finally, the environmental impact of the two FPV systems are then compared to standard ground mounted fixed-tilt solar PV systems from the literature.

10-MW Foam-Based FPV Plant Design

The floating PV system in this study was designed using the open-source foam-based FPV temperature model proposed in a recent study [41,62]. The spreadsheet was adapted to evaluate the energy production and the water conservation potential of a 10-MW foam-based FPV plant installed on Lake Mead during its entire lifecycle [59]. The cooling effect of the water on the foam-based FPV is included in the temperature model. The data used for the simulation is historical hourly data collected in 2018 on Lake Mead by the United States National Oceanic and Atmospheric Administration (US NOAA) [63] and satellite data obtained from SOLCAST [64]. The annual PV degradation rate was applied to the energy produced during the first operation year to estimate a realistic total energy production of the system throughout its lifecycle. The water preservation potential of the foam-based FPV was estimated first on an annual basis, and extended to the lifetime of the plant. It should be noted that this is a conservative assumption due to the trajectory of global temperatures created by anthropogenic climate change [65–69]. The system parameters used in the study, the energy production, as well as the quantity of water saved are summarized in Table 1.

Life Cycle Inventory Analysis of a 10-MW Foam-Based FPV Plant

Table 2. Life cycle inventory of the LCA performed on the FPV system during its entire lifecycle.

Material	Quantity
110 W Flexible single crystalline photovoltaic modules	90,910
Mass of Solar PV Modules	181,820 kg
Polyethylene foam	10,710 kg
Polyurethane marine sealant	25,567 kg
Stainless steel zip-ties	982 kg
Anchoring concrete	450 kg
Metal chain	450 kg
Electric installation for 570kWp open ground PV system	18
500 kW Inverters	40

Foam-Based FPV Modules. The foam-based FPV module proposed by Mayville et al. [41,48] is made of a flexible SunPower SPR-E-Flex module [56], at the back of which polyethylene foam has been attached to ensure buoyancy of the module on the water surface. The modules were adhered to the foam surface using a rapid action waterproof polyurethane sealant. The modules are secured together by using stainless steel zip ties. The inventory used for the LCA of the 10-MW foam-based FPV system is shown in Table 2.

The flexible solar PV module consists of SunPower single crystalline silicon-based solar cells [56]. The cells have an STC efficiency of 23%. The chain of production of the solar module spans across three different locations. The manufacture of the solar modules begins by the production of single crystalline silicon wafers. The wafers are obtained through two transformation of metallurgical grade silicon. Metallurgical grade silicon is transformed into solar grade silicon using the modified Siemens process which is less energy intensive as compared to the regular Siemens process [6]. The solar grade silicon is further purified through the Czochralski process to yield single crystalline silicon ingots suited for photovoltaic cell manufacture [6,70,71]. The single crystalline silicon ingots are cut into wafers. The location considered for the production chain of the wafers in this study is China because China holds the largest share of the worldwide silicon production as of 2020 [72]. The wafers undergo a metallization process to obtain single crystalline Si solar cells [73]. In the case of SunPower flexible solar modules, the wafers are cut thinner (150 µm) [74] than wafers used in rigid single crystalline solar modules (170 µm) [75]. The thinness of the wafers enables the modules to have a flexibility of 30°. The flexible solar module used in this study are assembled in France [56]. The inventory data used for the manufacture of the flexible solar module originates from the 2020 report of the International Energy Agency (IEA) on the life cycle inventory data of solar PV systems [75]. This report updates a previous report that was published in 2015 [71]. The new data is used to update the existing inventory in SimaPro. Transportation between the different process locations, and

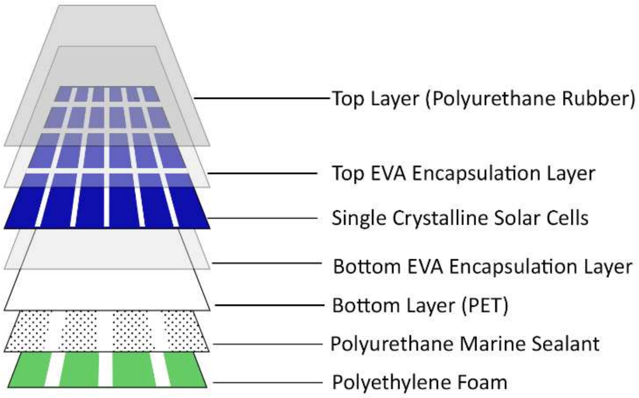

Figure 2. Exploded diagram of after-market modified foam-based floating solar PV module.

from the place of production (France) to the place of installation (Nevada, US) are included in the LCA.

PV Module Encapsulation Layers Analysis. The layout of the flexible module used in this study is made from top to bottom of a transparent layer, an ethylene vinyl acetate (EVA) layer, single crystalline solar cells, another layer of EVA, and a white layer; as shown on Figure 2. Flexible single crystalline solar PV modules are a rising technology, therefore there is no existing literature on the material inventory of the top and bottom layers of the module. In this analysis, the layers of the module have been examined using two different spectrometer techniques to acquire material data.

An attenuated total reflection (ATR) characterization has been run on a sample of the front transparent and back white layers in which the module is encapsulated**.** An iS50R (Thermo Scientific) Fourier transform infrared (FTIR) spectrometer was used for the analysis and was calibrated with the following parameters: 256 scans, 4 cm^{-1} of resolution, and a wavenumber bandwidth of 4000 - 650 cm^{-1} [76,77]. The resulting spectra were compared to possible matches in the iS50R software database. The front transparent layer belongs to the polyurethane rubber family and the back white layer was identified as polyethylene terephthalate (PET) polymer as displayed on Figure 3 and Figure 4. Polyurethane rubber (PUR)

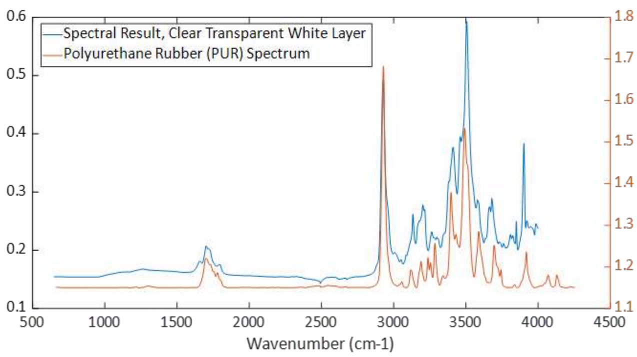

Figure 3. Spectral comparison of polyurethane rubber with the top clear layer of the flexible module.

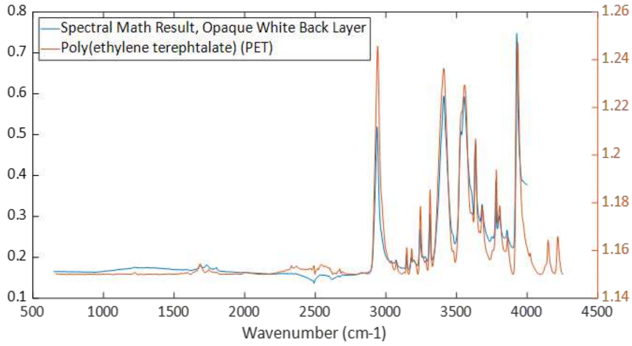

Figure 4. Spectral comparison of polyethylene terephthalate and the back white layer of the flexible module.

was proposed in the literature as a polymer that can be used for the front transparent surface of solar modules [78].

After the material composition of the two layers were determined, an FEI Philips XL 40 [79] environmental scanning electron microscope (ESEM) was used to measure the thickness of each layer as shown on Figure 5. The thickness of the materials is combined to the dimensions of the module (116.5 cm x 55.6 cm) [56] to calculate the volume of each material required for the assembly of a single module. The mass of the material used in the life cycle analysis is found by multiplying the volume of each material to the density of the material.

The life cycle inventory data of the module referenced in the international energy agency report describe the manufacture input for rigid single crystalline PV modules. The inventory data is updated using the measured data form the flexible module. The front glass, the aluminum frame, and the polyvinyl fluoride (Tedlar) used in a rigid solar PV module are replaced by polyurethane and polyethylene terephthalate. Additionally, the corners and the side of the module are pierced and hold stainless-steel grommets to simplify the installation procedure. The characteristics and mass balance of the different parts of a flexible solar module are shown in Table 3.

Foam-Based FPV Racking. The racking used for the foam-based FPV modules is made of foam, marine sealant, and zip ties. The foam and the marine sealant are applied after the acquisition of the solar PV module as shown on Figure 6. The mass of all the

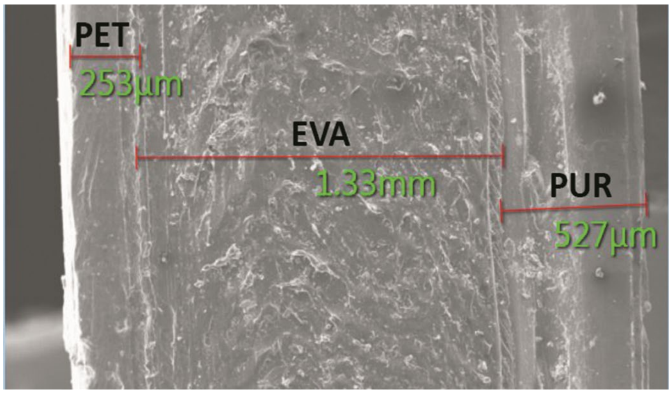

Figure 5. ESEM view of the thickness of the layers of the flexible module encapsulation.

Table 3. Characteristics and mass balance of the different layers of the flexible PV module.

Material	Thickness (µm)	Density (kg/m3)	Mass (g)
Polyethylene Terephthalate (Bottom Layer)	253	1380 [80,81]	226
Ethylene Vinyl Acetate (Solar Cells Encapsulation)	1330	948 [82,83]	817
Polyurethane Rubber (Top Layer)	527	1210 [78,84]	413
Monocrystalline Silicon Solar Cells	150	-	224
Grommets	-	-	4
Junction box, cables, and electronics	-	-	316
Total	-	-	2000

FPV racking components was determined with an open source digital scale with a precision of 0.05g [85].

The foam used to make the modules float on the water surface are made of polyethylene (PE) 1.2 lb ½" (12.7 mm) and was assumed to be manufactured in the U.S. For each module, 40 pieces of foam were used, each being 50 mm by 240 mm, resulting in a volume of PE of 6,096 cm^3 to ensure the floatation of a single module [41]. The density of the PE is 19.22 kg/m^3 [48]. The total mass of PE needed for each module is 118 g.

The foam pieces are adhered to the back of the module by a polyurethane marine sealant [86]. The quantity of marine sealant used for a single module was weighted and 281 g of adhesive were needed for each module. Polyurethane adhesive is manufactured by mixing in equal parts methylene-diphenyl-diisocyanate and polypropylene glycol [87]. These two materials were used in SimaPro to create the manufacturing process of the sealant.

Stainless steel zip-ties are used to limit the relative movement between neighboring modules and secure the modules on the water surface. Each module requires 10 zip-ties, two per corner grommet and one per side grommet. A single zip-tie weighs 0.82 g, therefore 8.2 g of zip-ties are needed for one module. The zip-ties have been assumed to be manufactured through metal casting.

Figure 6. After-market modification of a flexible solar PV module by taping PE foam on the back layer of the modules using polyurethane marine sealant

Electrical Components and Anchors. The electrical components of the plant that have been considered in this study are the inverters and the electrical installation of the cables. The native cables of the modules are waterproof because the modules are designed to be used in a marine environment. The native cable inventory is included in the module's inventory. Open ground installation inventory was used for the rest of the electrical installation connecting the string of modules to the inverter because there is no need to dig trenches for cabling in water. The open-ground electrical installation inventory that was used encapsulates the cables as well as the installation process. The material inventory used for the electrical installation and the inverters are found in SimaPro and originated from the Ecoinvent database [88]. The lifetime of the electrical installation was assumed to be 30 years and the lifetime of the inverters was assumed to be 15 years [71]. Therefore, the inverters need to be replaced halfway through the lifecycle of the system, and this was included in the LCA.

The anchoring of the system was considered to be a combination of concrete blocks and metal chain. The ratio of the anchor weight to the floating system weight is nearly 1:500 as found in boat anchors [89].

End-of-Life Scenario of the 10-MW plant

The end-of-life of the different equipment that went into the assembly of the foam-based FPV plant was factored into the life cycle assessment. The disposal of the inverters and the electrical installation is included in their respective life cycle inventory. The default waste treatment process included in the inverters and the electrical installation profile is incineration [54].

The current recycling process of crystalline silicon rigid solar modules consists of dismantling the modules and recovering material such as glass, aluminum, and copper while the rest of the material are landfilled or incinerated [90]. The end-of-life process of rigid crystalline solar PV modules is adapted to the flexible modules. In the case of flexible modules, the recovered materials are the copper from the wiring as well as the stainless steel from the grommets. The PUR is landfilled because landfilling remains the most common way to dispose of polyurethane [91] while the EVA, the PET, the solar cells and other electronic components are incinerated.

Regarding the foam-based racking of the FPV module, the polyethylene foam waste and the zip-ties are separated from the waste stream and recycled [92,93] while the polyurethane sealant is landfilled.

Impact assessment methods

Three major indicators have been investigated in this study: i) the energy payback time (EPBT), ii) CO_2 payback time (CO_2PBT), and iii) the water footprint.

When performing the LCA of an energy production system, it is important to evaluate the energy break-even time or energy payback time of the system. The energy payback time (EPBT) is defined as the period of operation time during which an energy production system will generate the same amount of energy as the primary energy that is required to manufacture, install, maintain, and decommission the system [5,24,25,71]. The EBPT in the case of the foam-based FPV module is calculated by dividing the total energy consumed during the lifecycle of the module by the annual energy production of the module as shown in Equation (1)

$$EPBT\ (years)\ = E_{cons}\ (kWh)\ /\ E_{an}\ (kWh/year) \qquad (1)$$

Where:

E_{cons} is the total energy consumed during the entire lifecycle of the floating FPV plant, from manufacture to disposal.

E_{an} is the average yearly energy production of the plant

The cumulative energy demand (CED) impact assessment method evaluates the direct and indirect energy consumption throughout the entire lifecycle of a product or process [55,94]. The CED has been used in this study to evaluate the energy consumption of the foam-based floatovoltaic plant.

Similarly, to the EPBT, the CO_2 payback time (CO_2PBT) is used to evaluate the number of operation years needed for a system to offset the total CO_2 emission during its lifecycle by its annual CO_2 emission reduction potential. It should be noted that substantial amounts of emissions occur at the end of the life cycle so care must be taken when using the CO_2PBT to do dynamic carbon emission analysis [95].

$$CO_2PBT\ (years) = \frac{CO_2\ life\ cycle\ (kg\ CO2\ eq)}{CO_2\ annual\ reduction\ (kg\ CO2\ eq/year)} \qquad (2)$$

The CO_2 emission reduction potential is location specific and depends on the electricity grid mix of the location of interest. In this study, the CO_2 emission reduction potential is calculated by multiplying the annual energy production of the power plant by the U.S. grid mix CO_2 emissions of 2019 (0.41 kg CO_2/kWh [96]). The life cycle CO_2 equivalent (CO_2 eq) emissions of the system is assessed by using the global warming potential over 100 years (GWP 100) method. The GWP 100 quantifies the effect of different greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and chlorofluorocarbons (CFCs) in terms of kg of CO_2 equivalent over a time period of 100 years [24,52,55,97–99]. It provides a uniform way of evaluating the global warming potential of the different greenhouse gases that are released during the lifecycle of a product or process [55,97].

Several studies have shown that floating solar PV modules have the potential to prevent water evaporation from lakes and reservoirs [38,42–44,100]. In order to identify how the water evaporation mitigation factors into the environmental footprint of the foam-based FPV module, the water scarcity indicator (WSI) proposed by Hoekstra et al. has been used to quantify the water footprint of the module [55,101]. This method has been preferred because it analyzes safe water sources depletion by combining socioeconomic and hydrological data [55,101] and the FPV module is intended to be installed on a lake surface. After the water footprint of the module is determined, it is compared to the water saving potential.

Sensitivity Analysis

Two major assumptions were made during the LCA of the foam-based FPV system: the lifetime of the flexible modules and the lifetime of the polyethylene foam. It is therefore crucial to analyze how the variation of these two parameters affects the life cycle impacts of the system. In the main analysis the lifetimes of both components were set to 30-years. The warranty provided by the module manufacturers on the flexible modules, however, is 5 years [56], even though conventional solar PV modules are known to last well-beyond 30 years [57,102]. It important to point out that the specific modules used in the FPV experiments in this study only had a 5-year warranty. There are, however, flexible PV modules in the same class that have more industry-standard 25-year warranties. For example, Renogy offers a long warranty based on output. It is at a 5 year/95% efficiency rate, 10 year/90% efficiency rate, 25-year/80% efficiency [103]. Here a 30-year timeline is used to represent the realistic lifetime of the modules and accounted for an 0.5% drop per year.

On the other hand, polyethylene is known to be able to remain intact in a marine environment for up to 15 years before the start of its degradation process [104], and water is known to accelerate the degradation as compared to air [105]. Therefore, the lifecycle impacts have been reassessed by varying the lifetime of the modules and the lifetime of the PE foam with a 5-years increment. In the case of the flexible modules, their replacement is always also accompanied by the replacement of the marine sealant. The sensitivity analysis is performed independently between the lifetime of the modules and that of the PE foam. For each iteration of the lifetime of the PE foam, a simulation is run over the lifetime range of the combination of flexible modules and sealant while the lifetime of the PE foam is maintained at a constant value. When the modules are replaced after a short period of time, their degradation rate is reset. This reset provides a slight boost in the energy production and has been factored in the sensitivity analysis. For each iteration of the lifetime, the average annual energy production as well as the lifecycle inventory quantities for the modules, the sealant and the foam are displayed in Table 4. The stainless-steel zip-ties are releasable and reusable [106], therefore their inventory as well as the inventory of electrical installation and

Table 4. Life cycle inventory of the flexible modules, marine sealant, and foam for different lifetimes ranging from 5 to 30 years.

Lifetime (years)	5	10	15	20	25	30
Flexible PV Modules (metric tons)	1,091	545	364	273	218	182
Marine Sealant (metric tons)	153	77	51	38	31	26
PE Foam (metric tons)	64	32	21	16	13	11
Average Annual Energy Generation (GWh/year)	23.1	22.8	22.5	22.2	21.9	21.7

inverters remained the same as in Table 2 throughout the sensitivity analysis.

Results

In all the three impact categories, the contribution of the concrete anchors as well as the metal chains were negligible compared to the other equipment of the system.

Energy Payback Time (EPBT)

The total energy consumption of the 10-MW floatovoltaic plant during its 30-years lifecycle (from natural resources extraction to disposal) is 28 GWh. The manufacture of the flexible solar PV modules has the greatest energy consumption and amounts to 85.4% (24 GWh) of the total energy consumption of the plant. The second highest energy intensive part of the plant is the lifecycle of the inverter with a total energy consumption of 2.64 GWh. The electrical installation as well as the foam-based racking accounts respectively for 3.01% and 2.36% of the overall energy consumption. The energy consumption of the disposal scenario is negative (-50 MWh) because of the negative allocation of the energy collected during the incineration of the equipment at the end-of-life (See Figure 7). Additionally, Figure 7 shows a detail view of the energy consumption of the foam-based racking. The total energy use of the foam-based racking

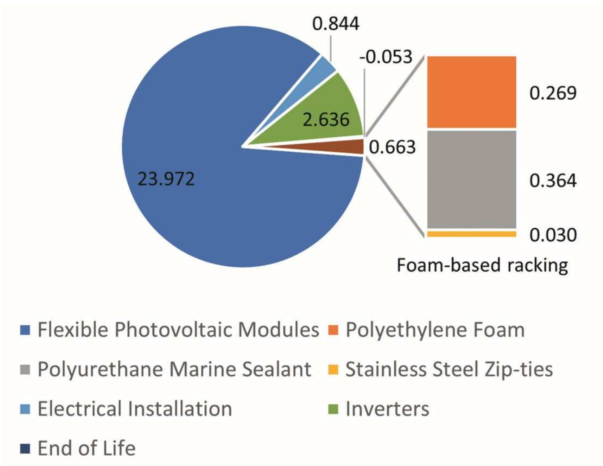

Figure 7. Detailed energy use results (in GWh) of the life cycle assessment of the 10-MW FPV plant using the CED method.

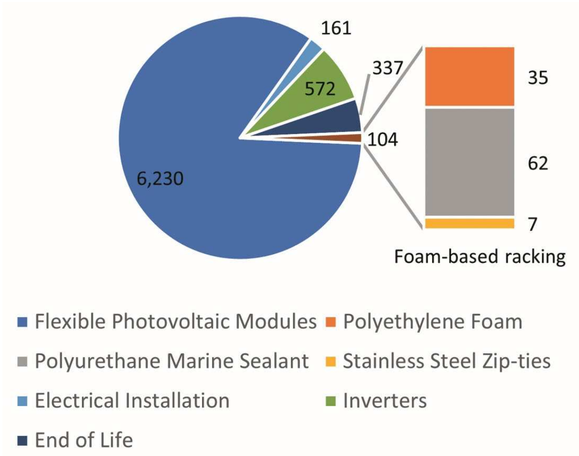

Figure 8. Detailed GHG emissions (in metric tons CO_2 eq) of the 10-MW foam-based FPV plant using the GWP method.

is 663 MWh, of which the manufacture of the polyurethane uses 55% while the polyethylene foam and the zip-ties use respectively 41% and 4%. The results of the EPBT calculation show that the foam-based FPV plant will offset its lifetime energy consumption in 1.3 years.

Co_2 Payback Time (CO_2PBT)

During the lifetime of the system, the total GHG emissions amount to 7,403 metric tons CO_2 eq. The life cycle stage that emits the most greenhouse gas is the manufacture, assembly, and transportation of the flexible solar PV modules. The GHG emissions of the modules are 6,230 metric tons CO_2 eq or 84% of the total GHG emission of the plant during its lifecycle as shown on Figure 8. The inverters have the second highest emissions (572 metric tons CO_2 eq) followed by the end-of-life, the electrical installation and the foam-based racking which respectively contribute 337; 161; and 104 metric tons CO_2 eq to the total GHG emission of the system. Figure 8 also displays a detailed emissions contribution of the different parts of the foam-based racking. Of the 104 metric tons CO_2 emitted by the racking, the polyurethane sealant accounts for 60% while the PE foam and the zip-ties respectively contribute 33% and 7%. The calculation of the CO_2PBT shows that the system can offset the total GHG emissions in 0.82 years.

Water Footprint

The water footprint simulation has shown that the total water usage during the life cycle of the system is 14 million m^3. The manufacture of the flexible PV leads the water consumption of the entire lifecycle (11.5 million m^3). The other notable components that consume a significant amount of water during its lifecycle are the inverters with a water use of 2.3 million m^3 as displayed in Figure 9. Figure 9 also shows the detailed total water consumption of the foam-based racking (190,000 m^3) and the manufacture of the zip-ties is leading the water use (83%).

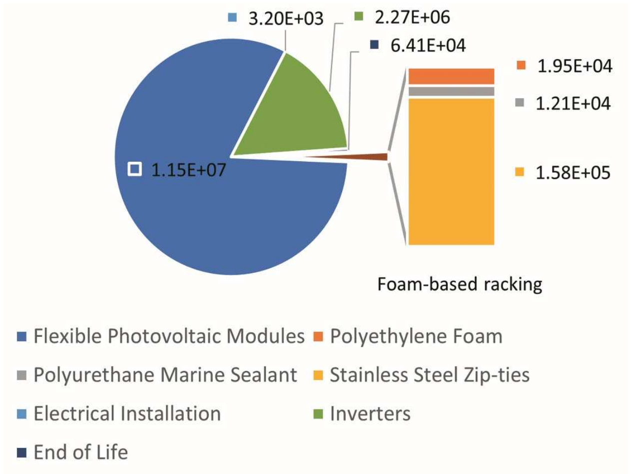

Figure 9. Detailed water footprint (in m3) of the 10-MW PV foam-based FPV plant using the WSI method.

Sensitivity results

The sensitivity analysis has shown that the lifetime of the foam does not have a significant effect on the three impact categories considered in this study. Figure 10 shows the results of the sensitivity analysis where the variation of the lifecycle metrics investigated in this study (GHG emissions, energy use, and water footprint) are plotted. The variations of the three metrics are plotted in groups, each group representing the effect of the lifecycle of the PE foam on the metric. Inside, each group is the variation of the metric regarding the lifecycle of the modules. As shown on Figure 10, there is no visible change from one group to the other due to the foam lifecycle, while the lifecycle of the modules greatly impacts the metrics inside each group. As an example, for a 30-year lifecycle of the modules, the GHG emissions are 7,480 metric tons CO_2 eq, the energy use is 28.3 GWh and the water footprint is 14.1 million m³, when the lifetime of the foam is 5 years. On the other hand, when the lifetime of the foam is 30 years, and the lifetime of the modules is maintained at 30 years, the GHG emissions are 7,400 metric tons CO_2 eq, the energy use is 28.1 GWh and the water footprint is 14.1 million m³. Figure 11 displays a detailed result of the effects of the lifecycle of the flexible modules on the GHG emissions to energy ratio (kg CO_2 eq/MWh), the energy use (GWh), the final water footprint (m³/MWh), the CO_2 payback time (years), and the energy payback time (years). In Figure 11, the sensitivity results of the effect of the module lifetime are shown for a PE foam lifetime of 15 years. According to the results, the lifetime of the modules has a significant influence

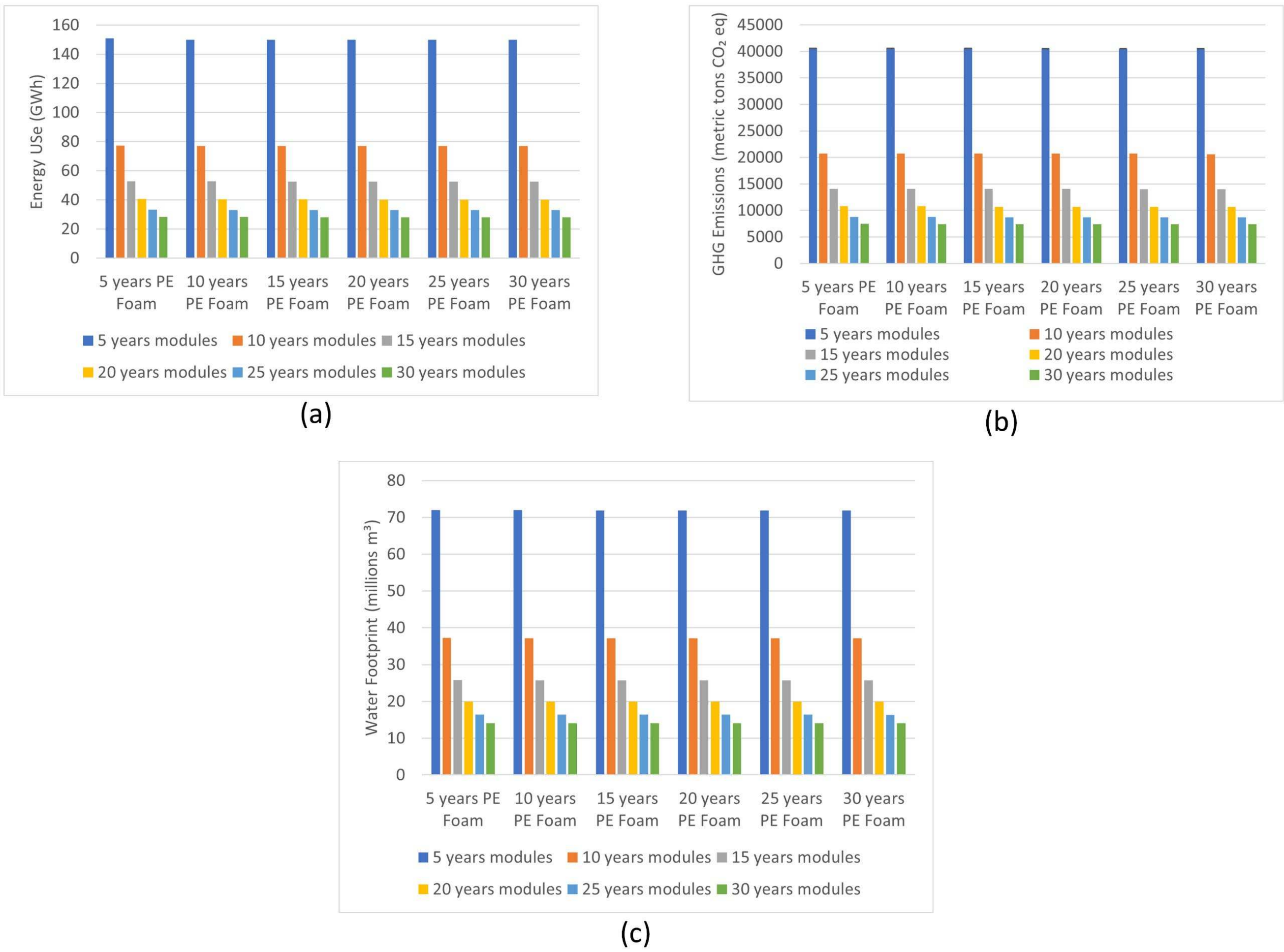

Figure 10. Sensitivity analysis results of lifecycle metrics. The metrics results are shown in groups for variation of PE foam lifetime ranging from 5 to 30 years. Inside each group, the metric result is shown for modules lifetime variation ranging from 5 to 30 years. (a) – Energy Use result using the CED method. (b) – GHG emissions results using the GWP method. (c) – Water footprint results using the WSI method

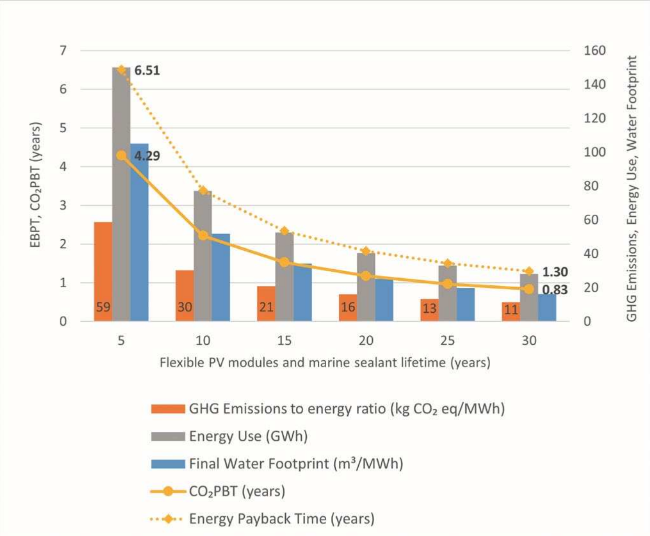

Figure 11. Detailed results of the impact of the variation of the modules lifetime (5 to 30 years) on the system lifecycle impact categories, for a PE foam lifetime of 15 years.

on the life cycle impact. When the lifetime of the modules is set to 30 years, the EPBT is 1.3 years, the CO_2PBT is 0.83 years, the final water footprint is 16 m³/MWh, and the GHG emissions to energy ratio is 11 kg CO_2 eq/MWh. When the modules are disposed of and replaced every 5 years, the EPBT is 6.51 years, the CO_2PBT is 4.29 years, the final water footprint is 105 m³/MWh, and the GHG emissions to energy ratio is 59 kg CO_2 eq/MWh.

Discussion

The life cycle analysis performed in this study has shown that over the course of 30 years, a 10-MW foam-based floating PV plant installed on the surface of Lake Mead would require a total energy input of 28 GWh, would emit 7,403 metric tons CO_2 eq of greenhouse gases, and would use up 14 million m^3 of water when the lifetime of the flexible modules are 30 years. At the same time, the system generates 650.3 GWh of clean electricity while preventing the evaporation of 3.4 million m^3 of water from the Lake reservoir.

Consequently, a foam-based FPV system installed on a water surface located in a tropical or subtropical climate zone, such as the climate zone where Lake Mead is located, would require 43 MWh of primary energy for every 1 GWh of clean energy generated, or an energy ratio between its primary energy use and its actual energy generation of 43 kWh/MWh. The energy payback time is evaluated at 1.3 years. This indicates that the foam-based FPV system will generate up to 23 times the energy it consumes during its entire lifecycle. Recent LCA studies during the past decade have shown that the EPBT for rigid c-Si solar PV plants ranged between 0.91 years to 6.05 years depending on the location and the encapsulation technology used for the modules [7,19,21,24,25,107,108]. The EPBT obtained in the current study (1.3 years) is located on the lower spectrum of these values even though the tilt of the modules considered is not optimal for the specified location. The foam-based modules have a tilt angle of 0° since they are lying flat on the surface of the water, whereas the optimal tilt of a PV system located near Lake Mead in Nevada would be 30° (latitude of 28°). The foam-based FPV modules have an EBPT close to that of conventional rigid modules made with aluminum back surface field solar cells (1.11 years [25]) because they benefit from an energy boost provided by the cooling effect of the water surface. Even though the energy production of foam-based solar PV modules located far away from the equator is hindered by the inclination factor, a recent study has shown that they can produce 3.5% more energy than expected from a module with an inclination of 0° at higher latitudes [41].

Similarly, for each GWh of clean energy generated, a foam-based solar FPV system located on Lake Mead will have a lifetime greenhouse gas emission of 11.38 metric tons CO_2 eq, corresponding to a GHG emission to energy generation ratio of 11 kg CO_2 eq/MWh. The CO_2PBT is less than a year being estimated at 0.82 year. This indicates that the foam-based FPV plant will offset 36 times the amount of CO_2 it generates during its lifetime. For comparison, the values of greenhouse gas emissions in the recent literature for rigid crystalline silicon modules were comprised between 12 kg CO_2 eq/MWh eq and 88 kg CO_2 eq/MWh [20,21,23,25,47,107–109]. It is important to point out that in the study where the lower value of 12 kg CO_2 eq was obtained, the authors did not perform a detailed life cycle assessment and the system boundary was not clearly specified [20]. Also, a study by Kim et al. has estimated the CO_2 payback time between 1.53 and 2.53 years which remains high compared to the result obtained in this study. Thus, the value of GHG emissions obtained in this study is the lowest value found in the literature to date. This indicate 30-years lifetime foam-based flexible solar FPV is the greenest crystalline based solar PV system to date when the flexible modules lifetime is 30 years. Cromratie Clemons et al. have estimated the CO_2 emissions of a pontoon-based FPV installed in Thailand to 73 kg CO_2 eq/MWh [46]. Several factors influence the GHG emissions of the foam-based FPV modules that were considered in this study. The mass of solar cells used to manufacture the flexible modules is lower than the mass required to manufacture a rigid module because the cells are cut thinner (150 µm for flexible module [74], 170 µm for rigid modules [75]). Also, the manufacture process of the flexible modules does not involve the use of glass or aluminum. Moreover, the simplicity of the racking used in the case of a foam-based FPV system is a key factor in the reduction of the GHG emissions. There is no concrete foundation or metal support involved in the manufacture of the foam-based floatation supports. All these factors result in a lower material use by the foam-based FPV system as compared to conventional PV systems, therefore, contributing to a reduction in the carbon emissions from the foam-based FPV system.

According to the simulation results, the water used by a 10-MW foam-based FPV plant located on the surface of Lake Mead in Nevada during its entire lifecycle is 14 million m^3. Therefore, the water footprint of a foam-based FPV plant installed on a water surface located in a tropical or subtropical climate zone is evaluated at 21.5 m^3/MWh. In comparison the water footprint of a pontoon-based FPV has been estimated to 110 m^3/MWh by Cromratie Clemons et al. [46], making foam-based FPV 5 times less water-intensive than pontoon-based FPV systems. On the other hand, a recent study has demonstrated that covering the surface of Lake Mead with foam-based floating PV has the potential to prevent water evaporation [41], specifically when the lake surface is covered by a 10-MW foam-based FPV, the system is able to save 3.4 million m^3 of water from evaporating. In terms of quantity of water saved per energy generated, the plant has the potential to prevent the evaporation of 5.2 m^3/MWh. This potential water saving offsets the water footprint of the system by reducing it from 21.5 m^3/MWh to 16.3 m^3/MWh. One advantage foam-based FPV assuredly has over conventional PV and pontoon-based FPV is the suppression of water usage during the operation phase of the system. A comparison of the water footprint from the manufacture phase of a flexible PV module and a rigid PV module performed in SimaPro using the water scarcity index method of Hoekstra et al. [101] has shown that the water footprint of rigid PV modules (568 m^3/m^2 of module) is 2.9 times greater than the water footprint of a flexible module (196 m^3/m^2 of module). Combining the fact that flexible modules have a lower water footprint than rigid modules, the fact that foam-based FPV systems do not consume water during their operation phase, and the fact that foam-based FPV substantially offsets its own water footprint by about 25% via reduced evaporation from the host water body, indicates that foam-based FPV have the best water footprint to date among crystalline silicon-based PV systems when the lifetime of the modules is 30 years. Because the foam-backed modules are in direct contact with the water surface, it should be mentioned that the reduced evaporation and change in albedo due to the FPV could contribute to increased heating of the lake. This calculation is not straightforward because it depends on the surface albedo of the lake and the absorption coefficient of the water throughout the year and future experimental work is needed to quantify these variables. It should be pointed out that roughly a fifth of the energy that would normally be absorbed by the lake water is instead extracted via conversion to electricity, so even if the surface albedo decreased because of the FPV leading to local increases in surface temperature, this effect is dampened by the electrical energy reduction.

The sensitivity analysis has shown that even though the results are not affected by the lifetime of the PE foam, the lifecycle impacts of a flexible FPV plant are sensitive to the lifetime of the modules. When the lifetime of the modules was varied down from 30 to 5 years with a 5-year decrement, the range of the impacts was 1.3 to 6.5 years for the EPBT, 0.83 to 4.29 years for the CO_2PBT, 11 to 59 kg CO_2 eq/MWh for the GHG emissions to energy ratio, and 16 to 105 m^3/MWh for the final water footprint. When the flexible modules have to be replaced every 5 years, corresponding to the manufacturer's warranty, the EPBT (6.5 years) is higher than the value (4.65 years) reported by Kim et al. using single crystalline silicon rigid modules [24]. This indicates, however, that the foam-backed-FPV modules are not advantageous from an energy perspective although they are from GHG emissions stand point. For the foam-based flexible FPV system to be at least as EPBT-efficient as the value of 4.65 years, the lifetime of the modules needs to be greater than 7.4 years. Nevertheless, even when the lifetime of the flexible modules is set to 5 years, which is the warranty offered by the manufacturer, they appear to have a lower GHG footprint (59 kg CO_2 eq/MWh) than the high value reported in the literature (88 kg CO_2 eq/MWh [23,108]). Furthermore, a reverse analysis on the GHG emissions shows that the foam-based FPV system would emit as much greenhouse gases as the lowest value found in the literature (12.3 kg CO_2 eq/MWh [20]) when the lifetime of the panels is set to 26.6 years. This analysis shows that for foam-based FPV to be assuredly the greenest FPV to date, the lifetime of the modules needs to be at least 26.6 years.

The study has covered the life cycle analysis of a 10-MW foam-based FPV plant and has shown that foam-based FPV has the potential of becoming the greenest type of solar PV in an industry already well-respected for being one of the greenest forms of electricity production. By reducing the components involved in the balance of system as well as by using lighter solar PV modules, the energy requirement and GHG emissions associated with crystalline solar PV are greatly reduced. It is challenging to exactly quantify by how much foam-based FPV improve the environmental impacts of the solar PV industry because the results of a life cycle assessment vary depending on the location. The focus of the current study has been to determine the life cycle inventory of the newly proposed design of a foam-based FPV system and compare that with existing values from the literature for land-based solar PV systems and pontoon-based FPV systems. It should be noted that these studies have different system boundaries and locations. Therefore, future work is needed to run a complete comparative life cycle assessment of a foam-based flexible FPV system, a pontoon-based FPV system, and a land-based PV system using the same system boundaries; ideally using all experimental values as inputs. A particularly interesting case to examine is the comparison of foam-based flexible FPV and land-based PV using flexible modules and alternative racking system. Further studies are also needed to evaluate the impact of the location and the recycling process on the different PV systems.

Another challenge that needs to be addressed by future studies is the testing of the durability of the foam-based racking in different aquatic environments. As FPV systems are a relatively new technology, there is little information regarding the maintenance process of the system [110]. This is particularly true for foam-based FPV because this technology is still at the research phase. Nevertheless, as any other energy production system, FPV systems must undergo preventive and corrective maintenance during their operation phase. Pontoon-based FPV systems require cleaning during the operation phase, but in the case of foam-based FPV, the modules are semi-submerged, therefore cleaning is not an issue. The most important maintenance aspect in the case of foam-based FPV would be to ensure the integrity of the foam, the anchoring system, as well as the modules in a marine environment. In this study, the flexible PV, the polyethylene foam, the polyurethane marine sealant, as well as the stainless-steel zip-ties have been assumed to have a lifetime of 30 years and the results have shown that for foam-based FPV to be the greenest crystalline silicon based solar PV system to date, the lifetime of the modules needs to be at least 26.6 years. Therefore, the durability of these core components, especially the solar modules, needs to be tested experimentally and the impact of using different type of sealant, foam, or zip-ties can be explored as well as encapsulation methods for the flexible PV modules. Future study is also needed to develop a complete maintenance profile for FPV systems.

Because foam-based flexible PV modules are a new technology, there is no available data from the module manufacturers regarding the life cycle inventory, which have been adapted from the recent values of the life cycle inventory of rigid crystalline silicon modules. This assumption is the core assumption in the article, but it should be noted that foam-based FPV have a net positive impact on the environment in terms of EBPT and CO_2 emissions as long as they last even a year, which has already been experimentally verified in the course of seasonal deployments when obtaining the experimental data to do this analysis. In, future studies, along with testing for the durability of the flexible modules, consultations with flexible module manufacturers would be beneficial to get a more in-depth understanding of the life cycle inventories of the modules, and the foam-based FPV system as a whole. Not only do foam-based FPV appear to be the greenest crystalline silicon-based PV to date, when the lifetime of the modules is at least 26.6 years, as shown by the results of this study, a recent study has also determined that using foam-based racking could reduce the cost of racking by $0.37–$0.61/W as compared to pontoon-based racking or land-based PV racking [48]. Consequently, future work is needed to experimentally scale up foam-based FPV to investigate the real economic costs and viability of the system to find out the return-on-investment period of a foam-based FPV plant, as well as to compare the value of solar (VOS) [111] of the system to that of conventional PV systems.

To further improve the environmental performance of the foam-based FPV system, future studies need to perform accelerated testing of the system to demonstrate the overall lifetime, therefore reducing the material input for longer lifetimes. Also, the investigation of the recycling processes of the different plastic components that goes into the system design, as well as the use of recycled material for foam manufacturing are key factors to reducing the lifecycle impacts of the foam-based FPV system. Additionally, FPV systems are known to pair well with aquaculture to form aquavoltaic systems [112–114]. Future work is needed to investigate the LCA of a foam-based aquavoltaic system. The life cycle impacts of any solar PV system are location dependent because of the nature of the solar resource. This is even more applicable to FPV systems because they can only be installed at specific locations that have a water surface. Different locations worldwide depend on different energy production systems. Therefore, future studies should focus on the impact of the geographic deployment optimization impact on foam-based FPV systems by assessing the local water conservation needs as well as the type of energy sources that feed the local electricity grid.

Conclusions

This study has shown that the base case results for a foam-based FPV system, where the lifetime of the modules was 30 years, is one of the lowest energy payback times (1.3 years) in c-Si solar PV technologies reported to date. It also represents the lowest GHG emissions to energy ratio (11 kg CO_2 eq/MWh) to date among the same type of PV material technologies. In addition, the foam-based FPV system also had 5 times less water footprint (21.5 m^3/MWh) as compared to a conventional pontoon-based FPV (110 m^3/MWh). The lifetime of the foam-based racking does not affect the result while the lifetime of the modules has a significant effect on the lifecycle impacts of the foam-based plant. Therefore, foam-based FPV has a net positive impact on the environment in terms of EBPT and CO_2 emissions if its lifetime is above 7.4 years and the technology has the potential to become the greenest crystalline silicon-based solar PV technology if the lifetime of the modules can be guaranteed for at least 26.6 years. Future work is needed to determine the lifetimes of the system's components.

Author Contributions

Conceptualization: KSH, JMP; Data curation: KSH, PM; Formal Analysis: KSH; Funding acquisition: JMP; Investigation: KSH; Methodology: KSH; Resources: JMP; Supervision: JMP; Validation: KSH, PM, JMP; Visualization: KSH, PM; Writing – original draft: KSH, JMP, Writing – review & editing: KSH, PM, JMP

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors would like to acknowledge technical support from K. Perrine. This work was supported by the Witte and Thompson Endowments.

Notes and references

All the data used in the study, including the life cycle inventory, the electrical design parameters and the water saving calculations, are stored in an Open Source Framework repository available for download here: https://osf.io/qt6mx/

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