Environmental Impact of Global Warming Potential and Cumulative Energy Demand – A Study on Life Cycle Assessment of Floating Solar Photovoltaic Project at Kanigiri Reservoir, SPS Nellore District, Andhra Pradesh, India

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Abstract- Floating solar photovoltaic (FSPV) systems have emerged as a sustainable solution to address rising global energy demands while alleviating land-use constraints and enhancing water conservation. By installing solar panels on water bodies, these systems offer operational benefits such as improved panel efficiency and reduced surface evaporation. However, despite their environmental promise, FSPV systems entail significant upstream environmental burdens, particularly during manufacturing and material procurement. A comprehensive Life Cycle Assessment (LCA), aligned with ISO 14040 and 14044 standards, is thus essential to evaluate the full environmental footprint of these technologies. This study conducts a cradle-to-grave LCA for two proposed FSPV projects in India: a large-scale 3522 MW system in Nellore district and a mid-scale 459 MW system in Kanigiri reservoir. The environmental impacts are analysed using two indicators, that is Global Warming Potential (GWP) and Cumulative Energy Demand (CED). Results consistently identify PV module manufacturing, aluminium framing, and glass as the dominant contributors across all impact categories. The study highlights the importance of upstream design optimisation and material efficiency in reducing environmental burdens. These findings provide critical insights to support sustainable policy formulation, project planning, and material selection in the growing FSPV sector.

Keywords: Floating solar photovoltaic, Life Cycle Assessment, Global Warming Potential, Cumulative Energy Demand.

1. INTRODUCTION

The global shift towards renewable energy has positioned solar photovoltaic (PV) systems as one of the most promising technologies for sustainable electricity generation(Divine Sharon et al., 2023). Among recent innovations in this domain, floating solar photovoltaic (FSPV) systems have emerged as a viable alternative to land-based installations(Trapani &RedónSantafé, 2015). These systems involve deploying solar panels on buoyant structures over water bodies such as lakes, reservoirs, and canals. Apart from alleviating land scarcity issues, FSPV systems offer operational benefits including reduced panel temperature, higher efficiency, and lower dust accumulation. They also contribute to water conservation by limiting surface evaporation, which is particularly beneficial in arid and semi-arid regions(Jin et al., 2019).

As the installed capacity of floating solar has expanded rapidly rising from about 3 GW in 2020 to more than 13 GW by 2022, surpassing a prediction of 10 GW by 2025 (SOLAR, 2019),the need for comprehensive environmental evaluations has become increasingly important. Although solar PV technologies are known for their negligible operational emissions, the upstream and downstream stages of their life cycle spanning raw material extraction, manufacturing, transportation, installation, operation and maintenance, and decommissioning are associated with measurable environmental impacts. These include emissions of greenhouse gases, significant energy and water use, and the depletion of mineral resources(Arbaoui et al., 2025). Assessing these impacts requires a structured methodological approach that captures the full life cycle profile of the system.

Life Cycle Assessment (LCA), standardised under ISO 14040 and 14044, serves as an effective tool for evaluating the environmental performance of technologies throughout their entire lifespan (International Organization for Standardization, 2006);(Tam et al., 2022). LCA allows for the quantification of environmental indicators across all life cycle stages, ensuring that sustainability claims are backed by robust data. While land-based PV systems have been extensively analysed using LCA methods, floating solar systems remain relatively underexplored, particularly when it comes to regional and project-specific assessments. Most available studies focus on limited impact categories, often centred solely on greenhouse gas emissions, without considering the broader implications on energy demand, water use, and resource depletion((NREL), 2013). This narrow perspective limits the capacity of decision-makers to develop environmentally optimised deployment strategies.

The situation is further complicated by the lack of location-specific life cycle assessments for FSPV systems, particularly in the Indian context(Nallapaneni et al., 2020). Despite the increasing scale of installations across various regions, studies evaluating the environmental impacts of floating solar projects in places such as Nellore district and the Kanigiri reservoir in Nellore district have yet to be conducted. Without such assessments, there is limited clarity on how these region-specific deployments perform across critical environmental dimensions or how they compare with one another in terms of sustainability performance(Suzuki, 2025).

2. NEED FOR THE STUDY

This study presents a full-spectrum life cycle assessment of floating solar photovoltaic systems of Nellore district as a whole and of a specific location within it namely the Kanigiri reservoir, with significantly different installed capacities. It assesses environmental performance using two key indicators: Global Warming Potential (GWP)(Shanbhag et al., 2024) and Cumulative Energy Demand (CED)(Chen et al., 2025), These indicators collectively provide a holistic understanding of the system's climate impact, energy efficiency, water consumption, and mineral resource use. By covering all life cycle stages from cradle to grave, the study offers insights into both the environmental advantages and the improvement opportunities inherent in the FSPV approach. The results are intended to support more sustainable planning and execution of floating solar projects, contributing to informed decision-making in the broader transition to renewable energy systems.

3. LITERATURE REVIEW

Most available research focuses on generic, global averages and lacks site-specific resolution. Studies conducted by institutions such as the International Energy Agency's PVPS programme,

1. (NREL), 2024-Fraunhofer ISE, and the National Renewable Energy Laboratory have established baseline LCA values for standard PV systems, yet regional variations in material sourcing and energy potential are often overlooked. A limited number of studies have begun to explore the life cycle impacts of floating solar, indicating that while the floating structures introduce additional material requirements such as high-density polyethylene (HDPE) for pontoons and steel for anchoring the overall environmental impact remains comparable to or slightly lower than that of land-based systems when water savings and cooling effects are considered.
2. Moreover, some innovative designs, such as foam-based floating structures, have demonstrated substantial reductions in both water footprint and embodied carbon(Academia.edu, 2024).
3. In the Indian context, LCA studies on solar energy systems are still in a developing phase. While some of the assessments have been carried out for ground-mounted PV installations in specific states, floating solar remains a nascent field of study (Dzamesi et al., 2024).
4. Few published works provide detailed LCA metrics beyond carbon emissions, and fewer still examine cumulative energy demand, water use, or abiotic depletion (Nallapaneni et al., 2020).
5. This gap restricts the ability to draw conclusions relevant to large-scale deployments in specific environmental and policy contexts(Johansson & Goldemberg, 2012).
6. Given the rapid expansion of FSPV systems in India, particularly in southern states where water reservoirs are plentiful and land-use pressures are high, there is a clear need for detailed, location-specific environmental assessments(Kumar & Singh, 2022).

The absence of comprehensive LCA studies for floating solar projects in regions such as SPS Nellore district and the Kanigiri reservoir represents a critical void in the literature. Without empirical data from these regions, policymakers and planners lack the evidence base required to make informed decisions regarding sustainability optimisation, material selection, and long-term environmental trade-offs. This literature review therefore establishes the rationale for undertaking a detailed LCA across multiple impact categories and regional contexts to address the knowledge gap and support responsible deployment of floating solar technologies.

4. OBJECTIVES OF THE STUDY

The Primary objective of the Study is to assess the environmental impact of the FSPV project at Kanigiri Reservoir in SPS Nellore district, Andhra Pradesh.

The Secondary Objects are:

1. To analyse and find the impact of the environment through the assessment of Global Warming Potential tool.
2. To analyse and find the impact of the environment through the assessment of Cumulative energy Demand tool.

5. METHODOLOGY OF THE STUDY

This study adopts a cradle-to-grave life cycle assessment (LCA) framework to evaluate the environmental performance of floating solar photovoltaic (FSPV) systems across multiple impact categories. The methodology adheres to the principles outlined in ISO 14040 and ISO 14044 standards, ensuring a consistent and comprehensive evaluation of environmental burdens throughout all life cycle stages(Tam et al., 2022);(International Organization for Standardization, 2006). The functional unit selected for the analysis is one megawatt (1 MW) of electricity generated, which enables comparison of results across installations of varying sizes. This unit also allows for the normalisation of environmental impacts and facilitates meaningful interpretation of results relative to energy output.

The system boundaries encompass the full life cycle of the FSPV system, including upstream processes such as raw material extraction, manufacturing of photovoltaic modules and floating structures, transportation to the site, system installation, operation and maintenance over a 25-year lifespan, and eventual decommissioning and disposal. All components critical to the functioning of the system are considered within these boundaries, including the PV modules, aluminium frames, HDPE floats, anchoring and mooring structures, inverters, copper wiring, and associated balance-of-system materials. Site preparation is assumed to be minimal given the floating nature of the deployment, and end-of-life scenarios are modelled with no material recovery to provide a conservative estimation of environmental impacts.

Primary data related to system design, installed capacity, and material quantities were obtained from project documentation and technical reports associated with the two study sites—Nellore district (3522 MW) and Kanigiri reservoir (459 MW). Secondary data, including emission factors, energy intensity values, and water usage coefficients, were sourced from reputable databases and publications such as the North American Industry Classification System (NAICS), the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), Fraunhofer ISE, and the National Renewable Energy Laboratory (NREL). These sources provided consistent life cycle inventory (LCI) values across materials and processes, ensuring methodological rigour and comparability with international benchmarks.

Two key environmental indicators were used to characterise the performance of the FSPV systems: Global Warming Potential (GWP), measured in kilograms of CO_2-equivalent per MWh; Cumulative Energy Demand (CED), expressed in megawatt-hours equivalent (MWh-eq) per MWh; These indicators were selected to capture a comprehensive range of environmental impacts, covering climate change, resource efficiency, freshwater use, and mineral resource depletion.

To compute the GWP, material-specific quantities for each system component were multiplied by their corresponding emission factors, and the total emissions were aggregated across all life cycle stages. CED was determined by summing the energy inputs for each process stage—module production, floatation system manufacturing, inverter assembly, cable production, transportation, installation, operations, and end-of-life treatment—then dividing the total by the estimated energy output over the system's lifetime.

The water footprint was calculated by applying published water use coefficients for each life cycle stage, particularly manufacturing, which dominates water consumption due to the production of silicon wafers and polymer-based materials. Transportation, installation, and maintenance contributed minimally

to the total WF. The ADP was assessed by applying elemental depletion factors to the quantities of key raw materials such as aluminium, silicon, copper, and steel, reflecting the scarcity and extraction intensity of these resources. All indicators were computed for both individual system components and total system performance, allowing for disaggregated analysis and hotspot identification.
The results were visualised through a combination of tables and figures. While some tables containing numerical data were retained in their original tabular form, others were converted into bar or pie charts to better illustrate trends and material contributions. This methodological structure provides a robust basis for comparing the environmental performance of floating solar systems at different scales and locations, and it ensures that the findings are applicable for both technical analysis and policy development.

6. ASSESSMENT TOOLS OF ENVIRONMENTAL IMPACT:

6.1 Global Warming Potential (GWP)

The Global Warming Potential (GWP) indicator quantifies the total greenhouse gas emissions expressed in kilograms of CO_2-equivalent per megawatt-hour (kg CO_2e/MWh) across the life cycle of the FSPV system. This metric reflects the contribution of each material and process to climate change and forms a core aspect of environmental impact assessment.

Table 1: GHG EMISSION PER MW OF FSPV PROJECT

S. no	Material	Quantity (kg/MW)	Emission Factor (kg CO2-eq/MW)	Actual tCO2e (tonnes)	Reference of Conversion Factor (NAICS)	Reference for conversion factor
1.	Silicon (PV cells)	550	23.595	12.97725	NAICS 331410 - Nonferrous Metal Smelting and Refining	(Bureau, 2024e)
2.	Aluminum (frames)	320	3680	1177.6	NAICS 331313 - Alumina Refining and Primary Aluminum Production	(Bureau, 2024d)
3.	Glass (module cover)	800	960	768	NAICS 327211 - Flat Glass Manufacturing	(Bureau, 2024b)
4.	EVA (Encapsulation)	100	270	27	NAICS 325211 - Plastics Material and Resin Manufacturing	(Bureau, 2024a)
5.	Polymer (HDPE Floats)	250	450	112.5	NAICS 325211 - Plastics Material and Resin Manufacturing	(Bureau, 2024a)
6.	Steel (Anchoring system)	400	920	368	NAICS 331110 - Iron and Steel Mills and Ferroalloy Manufacturing	(Bureau, 2024c)
7.	Copper (Wiring, Inverters)	50	185	9.25	NAICS 331420 - Copper Rolling, Drawing, Extruding, and Alloying	(Bureau, 2024f)

The emission profile per megawatt for the FSPV system is detailed, providing a breakdown of the greenhouse gas (GHG) contributions of each key material. This information is presented in Table 1, which outlines the specific emissions intensity of each material. As indicated in Table 1, aluminium exhibits the highest emissions intensity, with approximately 1177.6 tCO2e per MW. Following aluminium, glass is the second largest contributor to emissions, with 768 tCO2e/MW, largely due to its mass and the energy-intensive nature of its production.
Steel, which is used in anchoring and mooring systems, contributes 368 tCO2e/MW, as shown in Table 1. In contrast, materials such as EVA, copper, and HDPE have relatively smaller emissions contributions per unit capacity. The data within Table 1 highlights the significant differences in emissions intensity among the materials used in FSPV systems. These differences underscore the importance of material selection in efforts to mitigate the environmental impact of FSPV installations. The emission intensities in Table 1 become particularly important when considering the overall emissions of large-scale deployments. Optimising material choices and production processes can substantially reduce the global warming potential of FSPV systems.

Table 2:GHG EMISSION FOR3522 MW FSPV, FOR THE PROPOSED FEASIBILITY STUDY OF NELLORE DISTRICT

S.no	Material	Quantity (kg/MW)	Emission Factor (kg CO_2-eq/kg)	Actual tCO_2e per MW	Total tCO_2e for 3522 MW	Reference
1..	Silicon (PV cells)	550	23.595	12.97725	45,705.87	(Bureau, 2024e)
2.	Aluminium (frames)	320	3680	1177.6	41,47,507.20	(Bureau, 2024d)
3.	Glass (module cover)	800	960	768	27,04,896	(Bureau, 2024b)
4.	EVA (Encapsulation)	100	270	27	95,094	(Bureau, 2024a)
5.	Polymer (HDPE Floats)	250	450	112.5	3,96,225	(Bureau, 2024a)
6.	Steel (Anchoring system)	400	920	368	12,96,096	(Bureau, 2024c)
7.	Copper (Wiring, Inverters)	50	185	9.25	32,599.50	(Bureau, 2024f)
	Total	—	—	2,475.33	87,17,123.57	—

The significance of the emission intensities detailed earlier becomes evident when extrapolated to the full 3522 MW deployment in Nellore. The total greenhouse gas (GHG) emissions by material for this installation are presented in Table 2, offering a comprehensive view of the project's carbon footprint. As shown in Table 2, aluminium contributes the largest share of emissions, with over 4.14 million tonnes of CO2-equivalent emissions.

Glass follows as the second-largest contributor, accounting for 2.71 million tonnes of CO2-equivalent emissions, according to Table 2. Steel contributes significantly as well, with total emissions reaching 1.30 million tonnes of CO2-equivalent. The aggregated emissions profile in Table 4 reveals that just three materials—aluminium, glass, and steel—account for nearly 90 percent of the project's total life cycle GWP. Table 2 underscores the disproportionate impact of certain materials on the overall carbon footprint of large-scale FSPV systems. The dominance of aluminium, glass, and steel highlights where mitigation efforts can be most effectively focused. These findings emphasise the importance of material selection and life cycle considerations in the planning and execution of large solar installations. Reducing emissions from these key materials is crucial for minimising the environmental impact of FSPV projects.

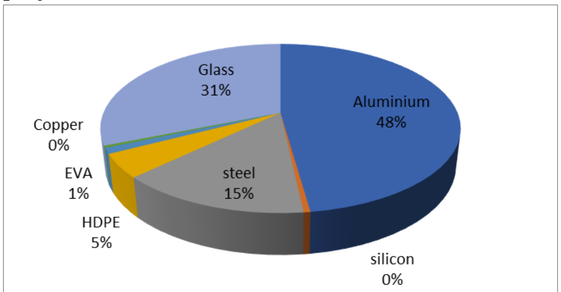

Figure.1:
GHG EMISSION FOR 459 MW FSPV PROJECT, FOR THE PROPOSED FEASIBILITY STUDY OF KANIGIRI RESERVOIR

The greenhouse gas (GHG) emissions for the 459 MW floating solar photovoltaic (FSPV) system at the Kanigiri reservoir are graphically presented. A breakdown of the GHG emissions by material for the Kanigiri installation is provided in Figure 1. As illustrated in Figure 2, aluminium is the dominant contributor to the overall emission profile of the Kanigiri system. Following aluminium, glass represents the second-largest source of GHG emissions, as shown in Figure 1.

Steel also contributes significantly to the total emissions, although to a lesser extent than aluminium and glass. Figure 1 effectively demonstrates the disproportionate impact of certain materials on the carbon footprint of the FSPV system. The visual representation in Figure 2 highlights the consistency of emission trends observed in the Nellore district project. These emission contributions, as depicted in Figure1, underscore the importance of material selection in mitigating environmental impacts. The data suggests that reducing emissions from aluminium and glass is crucial for lowering the overall GHG footprint of FSPV systems. Therefore, Figure 1 offers a clear visual comparison of the GHG emissions associated with different materials in the Kanigiri project.

The comparative analysis between Nellore and Kanigiri highlights three consistent GWP hotspots across both systems: aluminium, glass, and steel. These findings are in line with broader global LCA studies on PV systems, confirming that structural components are the primary sources of climate impact(Frischknecht et al., 2020; Raugei&Fthenakis, 2010a, 2010b). Opportunities for emissions reduction include sourcing aluminium from secondary (recycled) streams, optimising floatation system design to reduce overall material mass, and localising material procurement to reduce transport-related emissions.

Given the significant contribution of just a few materials, any intervention targeting these hotspots—such as process decarbonisation, improved manufacturing efficiency, or circular material flows—can yield substantial climate benefits. Therefore, material substitution and eco-design strategies should be prioritised in the development of large-scale floating PV projects.

6.2 Cumulative Energy Demand (CED)

Cumulative Energy Demand (CED) refers to the total primary energy required across the entire life cycle of the FSPV system. It includes both direct and indirect energy used in raw material extraction, component manufacturing, system assembly, transportation, operation, maintenance, and decommissioning. Expressed in megawatt-hours equivalent (MWh-eq) per megawatt of installed capacity, CED offers a comprehensive view of energy intensity beyond the operational phase of the system.

Table 3: CED PER LIFE CYCLE STAGE OF 1 MW

S.no	Life Cycle Stage	Energy Input (MWh-eq)	References
1.	PV Module Manufacturing	4,167	(IEA PVPS Fraunhofer ISE, 2017)
2.	Floatation System (HDPE)	1,250	(Europe, 2022)
3.	Inverter	333	(G. et al. IEA PVPS, 2020)
4.	Cables	167	(Ghosh et al., 2020)
5.	Anchoring & mooring	250	(I. IEA PVPS, 2017)
6.	Transportation	417	(IPCC DEFRA, 2006)
7.	Installation	167	(Ghosh., 2020)
8.	O&M over 25 years	333	(IEA PVPS NREL, 2016)
9.	Decommissioning/Recycling	167	(H. et al. IEA PVPS, 2017)
	Total	7,250 MWh-eq	

The energy requirements for each life cycle stage of a 1 MW FSPV system are detailed, providing a comprehensive view of energy consumption. This breakdown is presented in Table 3, which outlines the energy input for various stages, from manufacturing to decommissioning. As shown in Table 3, PV module manufacturing is the most energy-intensive stage, requiring 4167 MWh-eq. The floatation system (HDPE) is the second-largest energy consumer, with an energy input of 1250 MWh-eq, as indicated in Table 3.

Inverter production requires 333 MWh-eq, while cables, anchoring, and mooring systems have lower energy demands. Table 3 also illustrates that transportation and installation contribute moderately to the overall energy demand. In contrast, the operation and maintenance (O&M) and decommissioning/recycling stages have relatively low energy requirements. The data in Table 3 highlights that energy consumption is heavily concentrated in the manufacturing phases of the FSPV system's life cycle. These findings emphasise the importance of improving energy efficiency in the production of PV modules and floatation systems. Reducing energy inputs in the early stages can significantly decrease the overall energy footprint of FSPV installations.

Table 4:CED FOR 3522 MW FSPV PROJECT, FOR THE PROPOSED FEASIBILITY STUDY OF NELLORE DISTRICT

S.no	Life Cycle Stage	Energy Input (MWh-eq) per MW	Energy Input (MWh-eq) for 3522 MW	References
1.	PV Module Manufacturing	4167	14676174	(IEA PVPS Fraunhofer ISE, 2017)
2.	Floatation System (HDPE)	1250	4402500	(Europe, 2022)
3.	Inverter	333	1172826	(G. et al. IEA PVPS, 2020)
4.	Cables	167	588174	(Ghosh et al., 2020)
5.	Anchoring & mooring	250	880500	(I. IEA PVPS, 2017)
6.	Transportation	417	1468674	(IPCC DEFRA, 2006)
7.	Installation	167	588174	(al., 2020)
8.	O&M over 25 years	333	1172826	(IEA PVPS NREL, 2016)

9.	Decommissioning/Recycling	167	588174	(H. et al. IEA PVPS, 2017)
	Total	7251	25538022	

The energy consumption across each life cycle stage for the entire 3522 MW Nellore district installation is detailed, providing a comprehensive view of the project's energy footprint. These cumulative energy demands are presented in Table 4, offering a breakdown of energy input from manufacturing to decommissioning at a large scale. As Table 4 illustrates, PV module manufacturing is the most energy-intensive stage, requiring 14.68 million MWh-eq. The floatation system contributes significantly to the overall energy demand, with 4.4 million MWh-eq, as shown in Table 4.

Inverter production accounts for 1.17 million MWh-eq, highlighting its substantial energy consumption within the system. Table 4 also shows that transportation, installation, O&M, cables, anchoring and decommissioning contribute smaller but still significant amounts to the total energy demand. Collectively, the data in Table 4 reinforces that the upstream manufacturing processes dominate the energy profile of large-scale FSPV deployments. The information underscores that reducing energy consumption in module and floatation system manufacturing is critical for lowering the project's overall energy footprint. These findings suggest that improving manufacturing efficiencies and utilizing lower-energy materials can lead to substantial energy savings. Optimising energy use in these key stages is essential for enhancing the sustainability of large FSPV installations.

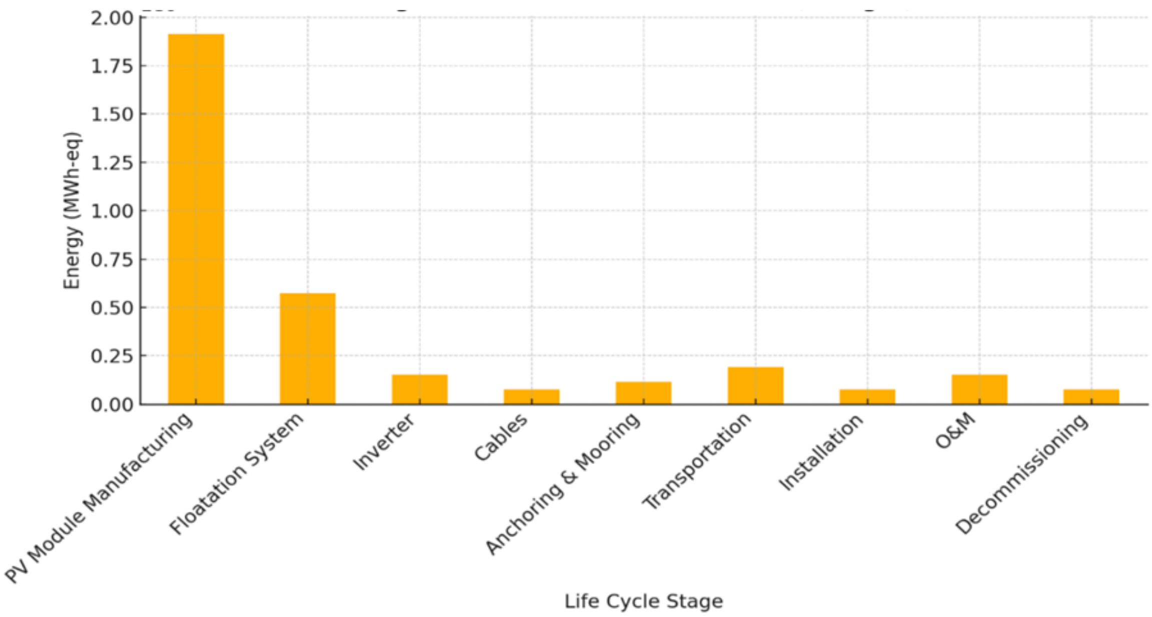

Figure 2:

CED FOR 459 MW FSPV PROJECT, FOR THE PROPOSED FEASIBILITY STUDY OF KANIGIRI RESERVOIR

The cumulative energy demand (CED) for each life cycle stage of the 459 MW floating solar photovoltaic (FSPV) system at the Kanigiri reservoir is visually presented. A breakdown of the energy input for each life cycle stage in the Kanigiri project is illustrated in Figure 2. As depicted in Figure 2, module manufacturing is the most energy-intensive stage in the Kanigiri system's life cycle. The floatation system also contributes significantly to the overall energy demand, as shown in Figure 2.

Inverters represent another notable portion of the total energy input, although less than module manufacturing and floatation systems. Figure 2 effectively demonstrates the distribution of energy consumption across different stages of the FSPV system. The visual representation in Figure 2 confirms the trend observed in the Nellore district project, where manufacturing dominates energy demand. These energy inputs, as shown in Figure 2, highlight the importance of focusing on manufacturing processes to improve energy efficiency. The data suggests that reducing energy consumption in module and floatation system production can substantially lower the system's overall energy footprint. Therefore, Figure 2 provides a clear visual summary of the energy demands associated with each life cycle stage in the Kanigiri project.

These findings highlight that reducing energy demand during manufacturing offers the greatest potential for improving the overall energy efficiency of floating PV systems. This could be achieved through cleaner energy inputs, process optimisation, and the use of recycled materials. Particularly, substituting virgin aluminium with secondary aluminium, and adopting polymer resins with lower energy intensity, could provide meaningful reductions in life cycle energy consumption.

Moreover, energy reduction strategies in the inverter and floatation stages can further improve system-wide performance. Regional manufacturing that taps into greener grid mixes, especially renewable-powered industrial hubs, can also contribute significantly to lowering CED. While operation and decommissioning are inherently less energy-intensive, their impacts may grow in relevance as system sizes increase and technologies evolve.

7. RESULTS AND DISCUSSION

The environmental performance of floating solar photovoltaic (FSPV) systems is fundamentally driven by the nature and quantity of materials employed throughout their life cycle. Each component contributes to the total environmental burden depending on its embodied energy, emissions profile, water use, and raw material extraction intensity. Understanding the material input baseline is essential for interpreting the life cycle impacts across all indicators.

Table 5: MATERIAL INPUTS PER MW INSTALLATION OF FSPV PROJECT

S.no	Material	Quantity (kg/MW)	Core raw material	Reference
1.	Silicon (PV cells)	550	Monocrystalline panels	(Silicon (PV Cell) - Monocrystalline Panels, n.d.)
2.	Aluminium (frames)	320	Based on FSPV structures	(Aluminium, 2025)
3.	Glass (module cover)	800	2-3 mm thick glass	(Flat Glass Manufacturing, n.d.)
4.	EVA (Encapsulation)	100	Ethylene Vinyl Acetate	(Plastics Material and Resin Manufacturing (EVA), n.d.)
5.	Polymer (HDPE Floats)	250	High-Density Polyethylene	(Plastics Material and Resin Manufacturing (HDPE), n.d.)
6.	Steel (Anchoring system)	400	Includes cables, clamps	(Iron and Steel Mills and Ferroalloy Manufacturing, n.d.)
7.	Copper (Wiring, Inverters)	50	Electrical system requirements	(Copper Rolling, Drawing, Extruding, and Alloying, n.d.)

The environmental performance of floating solar photovoltaic (FSPV) systems is significantly influenced by the materials used throughout their life cycle. The material inputs required for installing 1 MW of floating solar capacity are detailed in Table 5, which includes seven major components. These seven major components include silicon for PV cells, aluminium for frames, and glass for the module cover. Other materials listed in Table 5 are ethylene vinyl acetate (EVA) for encapsulation, high-density polyethylene (HDPE) for floatation, steel for anchoring and mooring, and copper for wiring and inverter integration. The quantities presented in Table 5 align with established benchmarks for floating PV systems.

Aluminium and glass constitute the majority of the system mass as shown in Table 5. The substantial use of aluminium and glass has implications for the system's life cycle impacts, given that both materials are energy-intensive to produce. Steel and HDPE are also significant components, particularly in the structural and floatation subsystems. The data illustrates the importance of addressing the upstream impacts associated with aluminium and glass. Optimising the use of these materials presents an opportunity to improve the sustainability of FSPV systems.

Table 6: TOTAL MATERIAL REQUIREMENTS FOR 3522 MW, FOR THE PROPOSED FEASIBILITY STUDY OF NELLORE DISTRICT

S.no	Material	Quantity (kg) for 3522 MW	Core Raw Material	Reference for Quantity
1.	Silicon (PV cells)	19,37,100	Monocrystalline panels	Silicon (PV Cell) - Monocrystalline Panels, n.d

2.	Aluminium (frames)	11,27,040	Based on FSPV structures	Aluminium, 2025
3	Glass (module cover)	28,17,600	2–3 mm thick glass	(Flat Glass Manufacturing, n.d.)
4.	EVA (Encapsulation)	3,52,200	Ethylene Vinyl Acetate	(Plastics Material and Resin Manufacturing (EVA), n.d.)
5.	Polymer (HDPE Floats)	8,80,500	High-Density Polyethylene	(Plastics Material and Resin Manufacturing (HDPE), n.d.)
6.	Steel (Anchoring system)	14,08,800	Includes cables, clamps	(Iron and Steel Mills and Ferroalloy Manufacturing, n.d.)
7.	Copper (Wiring, Inverters)	1,76,100	Electrical system requirements	(Copper Rolling, Drawing, Extruding, and Alloying, n.d.)

The material requirements for the full 3522 MW deployment in Nellore district are extrapolated to provide a comprehensive view of resource consumption at the regional level. These cumulative values are presented in Table 6, offering a detailed breakdown of the total material requirements. As shown in Table 6, the total quantity of silicon (PV cells) required for the 3522 MW project is 19,37,100 kg. The table also specifies that 11,27,040 kg of aluminium (frames) and 28,17,600 kg of glass (module cover) are required for the same project.

Table 6 further details the quantities of other materials, including 3,52,200 kg of EVA (Encapsulation) and 8,80,500 kg of Polymer (HDPE Floats). For the anchoring system, 14,08,800 kg of steel is required, and the requirements for copper (wiring and inverters) are 1,76,100 kg. The data in Table 6 reinforces that aluminium and glass constitute the majority of the system mass. These significant quantities of aluminium and glass have direct implications for the system’s life cycle impacts. The large-scale material requirements underscore the importance of addressing the environmental burdens associated with their production. Optimisation strategies for these materials are essential for improving the sustainability of large FSPV installations.

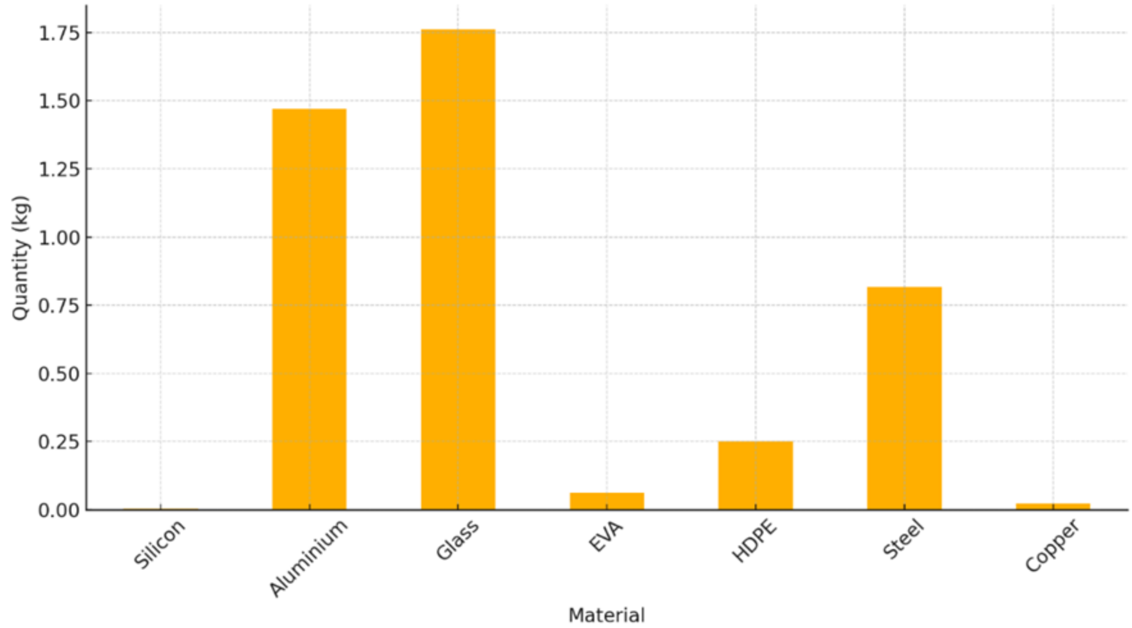

Figure 3:

Total Material Requirements for 459 MW, for the proposed feasibility study of Kanigirireservoir

The material requirements for the 459 MW floating solar photovoltaic (FSPV) project at the Kanigiri reservoir are visually represented to provide a clear comparison of material quantities. A breakdown of the total mass of each material component used in the Kanigiri project is illustrated in Figure 3. As shown in Figure 3, aluminium and glass constitute a substantial portion of the total material input for the Kanigiri system. The dominance of aluminium and glass, as presented in Figure 3, reinforces the findings from the Nellore district analysis.

Steel and HDPE also represent significant material inputs, although their quantities are less than those of aluminium and glass. Figure 3 effectively highlights the disproportionate contribution of certain materials to the overall mass of the FSPV system. The visual representation in Figure 3 underscores the critical need to address the upstream impacts associated with aluminium and glass. These material requirements, as depicted in Figure 3, have implications for the environmental footprint of the Kanigiri project. The data suggests that optimising the use of aluminium and glass could lead to more sustainable FSPV installations. Therefore, Figure 3 provides a clear visual summary of the material composition and its potential environmental significance.

The high proportion of aluminium and glass in both installations calls attention to the potential benefits of alternative material sourcing, lightweight design, and recycling. Since these materials are also major contributors to GWP, CED, and ADP, their optimisation represents a key opportunity to improve the sustainability of FSPV systems at scale.

8. CONCLUSIONS

Floating solar photovoltaic (FSPV) systems have emerged as a promising alternative to land-based solar installations, offering numerous environmental and operational advantages, particularly in water-scarce regions. However, despite their operational efficiency and contribution to land conservation, these systems are not devoid of environmental burdens, particularly during upstream stages such as material extraction and manufacturing. In this study a cradle-to-grave Life Cycle Assessment (LCA) of FSPV systems in SPS Nellore district, Andhra Pradesh, including a detailed evaluation of the 459 MW Kanigiri reservoir project, to quantify the environmental performance using two core indicators: Global Warming Potential (GWP) and Cumulative Energy Demand (CED), was conducted. Results reveal that GWP for 1 MW of installed capacity is approximately 2475.33 tCO_2e, with aluminium (1177.6 tCO_2e) and glass (768 tCO_2e) as the most significant contributors, cumulatively accounting for over 70% of total emissions. Similarly, the CED per megawatt was found to be 7250 MWh-eq, predominantly driven by module manufacturing (4167 MWh-eq) and HDPE-based floatation systems (1250 MWh-eq). When scaled to the 3522 MW Nellore project, these impacts translate into over 87 lakh tonnes of CO_2-equivalent emissions and 25.5 million MWh-eq of energy consumption. The findings clearly indicate that material selection—particularly for aluminium, glass, and polymers—plays a pivotal role in determining life cycle environmental performance. Substituting virgin materials with recycled inputs and adopting energy-efficient manufacturing methods can substantially mitigate these impacts. The study thus provides a robust environmental baseline to support sustainable planning and policy decisions in India's rapidly growing FSPV sector.

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