Suspension of photovoltaic panels over water canals ("Canalvoltaico"): technical feasibility, economic and environmental benefits of a Canal-Top solar plant installation in Emilia-Romagna, Italy

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Abstract: Solar energy has become an increasingly important part of the global energy mix. In Italy, the photovoltaic power installed has grown by 40% since 2015 and this raises the problem of land use and occupation. A viable alternative, already experienced in India, is placing solar panels on the top of water canals (Canal-Top, in Italian “*Canalvoltaico*”). It is a relatively new and innovative approach to solar energy installation that offers several advantages, including the potential to generate renewable energy without occupying additional land, reduce water evaporation from canals, and improve water quality by reducing algae growth. The article explores various canal-top solar projects over the world, then a viable application in the Italian region “Emilia-Romagna” is discussed, evaluating specialized designs, installation and maintenance costs, water evaporation reduction and the potential for conflicts with other water uses. Investment opportunities and risks are also discussed.

Keywords: renewable energy, photovoltaic, solar energy, water canals, canal-top solar, sustainability, canalvoltaico

I. Introduction

Photovoltaic (PV) energy has emerged as a prominent renewable energy source worldwide, offering a sustainable and environmentally friendly solution to meet the increasing global energy demand. According to the International Energy Agency (IEA), Italy ranks among the top ten countries in terms of cumulative PV installations, with an installed capacity of over 25 GW [1].

However, the rapid expansion of PV plants has led to concerns regarding the occupation of land, particularly in densely populated regions. The utilization of vast areas of land for solar panel installations has raised questions about its impact on agriculture, biodiversity, and land-use conflicts.

To address this issue, innovative approaches have been developed, one of which is the concept of agrivoltaic systems. Agrivoltaics integrates solar panels into agricultural areas, allowing for the dual use of land for both energy generation and crop cultivation.

In addition to agrivoltaics, another emerging solution to the challenge of land occupation by traditional ground-mounted PV installations is the concept of Canal-Top Solar PV plants (in Italian we devised the term “Canalvoltaico”). Canal-Top systems integrate solar panels on the surface of water canals, leveraging the dual benefits of solar energy generation and efficient use of land and water resources. This concept has gained popularity in recent years, offering a promising and sustainable alternative.

In the first part of the article, we aim to provide an overview of Canal-Top plants landscape around the world, highlighting the main features and examining the current state of these technologies.

Using the information gathered, the paper reports a preliminary feasibility study on the application of the technology in the Italian context, along the CER (Canale Emiliano Romagnolo) which is one of the most important artificial canals in Italy, in Emilia-Romagna region. The study reports technical and economic evaluations regarding the use of two different panel anchoring methods.

At the time of publication of this article, through our best research we have not found any other similar feasibility studies carried out in Italy. The paper therefore lays the foundations for further in-depth studies contributing to scientific and industrial research on this technology.

Figure 1. Maps of canal-top solar plants in the world

II. MATERIALS AND METHODS

A comprehensive literature review was conducted to examine the current status of solar PV plants installed on canals worldwide. The objective was to gather information on existing canal-top PV plants, including their design, performance, cost-effectiveness, and any identified challenges or criticalities. Based on the findings from the literature review, a case study was designed to assess the feasibility of placing solar PV panels on canals in Italy, in the Emilia-Romagna region. To evaluate the economic aspects of the proposed canal-top PV system, a comprehensive cost analysis was performed. This analysis involved assessing the capital costs associated with the installation of solar PV panels, support structures, electrical components, and other necessary infrastructure. Cost estimations were based on market prices, industry standards, and previous studies on solar energy systems. Water saving through reduction of evaporation were estimated through different equations from literature. Various aspects such as maintenance impacts and safety risks were examined.

III. A REVIEW OF CANAL-TOP SOLAR PLANT AROUND THE WORLD

Currently, there are only few canal-top solar systems installed in the world (figure 1). The first applications (2015) were made in India, in the regions of Gujarat and Punjab. Other applications can be found, also in the country, in the Dehradun region. Possible applications have also been studied in the United States, particularly in Arizona and California.

Two main types of structures supporting the panels can be observed:

1. steel truss structures, transverse to the course of the canal, with reinforced concrete supports on the quays.
2. suspense steel cable structures with supports on the quays or with supports directly inserted into the watercourse.

In the Gujarat region, the solarization project of the network has been called “Sardar Sarovar Solar Project”, from the name of the dam from which a massive canal system, stretching 71.748 kilometers into the region, originates [2] [3] [4] [5].

TABLE 1. Sardar Sarovar Solar Project

Map ref.	Region	Plant	Size	Structure
(1)	Gujarat	Pilot Plant	1 MW	Steel Truss
		New Sama	10 MW	Steel Truss
		Nimeta and Raval	10 MW	Steel Truss
		Nimeta and Raval	5 MW	Steel Truss
		Raval	10 MW	Steel Truss

In the Punjab region the Indian Ministry of Renewable Energy (MNRE) launched the “Pilot-cum-Demonstration Project” to set up pilot plants totaling 20 MW [6] [7]. The PV installed on the Punjab canals (figure 4) utilize a different technology than the others Gujarat projects (figure 2, figure 3), using cables and guy wires (suspension cable technology).

Figure 2. Pilot plant steel truss structure

Figure 3. New Same steel truss structure

The quays are therefore not an area for the construction of plinths or for covering with panels. Therefore, only the area above the watercourse is used, leaving the quays free.

The projects are gathered in the table below:

TABLE 2. Punjab's canal-top projects

Map ref.	Region	Plant	Size	Structure
(2)	Punjab	Ghaggar Link, Patiala	7.5 MW	Suspense Cable
		Ghaggar Branch, Nidampur	7.5 MW	Suspense Cable
		Ghaggar Branch, Nidampur	2.5 MW	Suspense Cable
		Sidhwan Branch, Dioraha	2.5 MW	Suspense Cable

Figure 4. Ghaggar branch canal-top plant

The PV installations in figure 5 is the Yamunua Canal, in the Dehradun region represent the world's largest tensile structures for supporting photovoltaic panels (the width of the canal reaches 37 meters) [8].

TABLE 3. Yamunua Canal Project

Map ref.	Region	Plant	Size	Structure
(3)	Dehradun	Yamunua Canal Plant	16 MW	Suspense Cable

Figure 5. Suspension cable structures on Yamunua Canal

We have not identified any other plants currently operating in the world. There are, however, projects under evaluation in the United States.

We report the result of the pre-feasibility study commissioned in 2015 to evaluate the solarization of the CAP (Central Arizona Project) [9]. The study proposes a technical analysis and a preliminary cost analysis, assuming the installation of 1 MWp on a section of canal oriented to the solar incidence.

TABLE 4. Central Arizona Project

Map ref.	*Region*	*Plant*	*Size*	*Structure*
(2)	Arizona	Pilot Plant, CAP (not operating)	1 MW	Steel truss

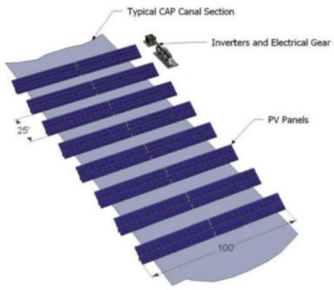

Figure 6. Solarized section of CAP

The estimated costs for the construction of the 1 MWp 'pilot' section is 4.488.750 $. Costs for power transmission, O&M for the canal and panels, and possible equipment replacement are not considered. The reduction in evaporation for the pilot section was estimated at 7,400 cubic metres (about 3 Olympic-size swimming pools). The study expresses a negative opinion on the realization of such a project, pointing out that the costs are significantly higher than for a ground-mounted photovoltaic field.

In California, the The Turlock Irrigation District (TID), the first irrigation district in California, has decided to launch a pilot project with a view to the subsequent massive solarization of the Californian canal network. The pilot project is called Project Nexus in reference to the water-energy nexus paradigm that is gaining attention among utilities [10]. No technical information about size and structure are available.

TID has started the project in the autumn of 2022. Full completion of the project is expected by the end of 2023. No further data are currently available.

IV. ANALYSIS OF THE CANAL-TOP PV APPLICATION IN EMILIA-ROMAGNA: CER CASE STUDY

After going through the various examples found in the literature from around the world, as reported in the previous paragraph, we hypothesized a case study in our region, Emilia-Romagna, along the Canale Emiliano Romagnolo (CER). This analysis requires to consider construction assumption and the associated costs, and maintenance and safety considerations.

The CER is one of the most important hydraulic works in Italy [11]. By deriving water from the Po River, it ensures the supply of water to 4 provinces, starting in the province of Ferrara and ending in the province of Rimini, with a total length of 135 km. Its flow rate progressively decreases along the route, decreasing from 60 m3/s to 6 m3/s in the final phase. The structure of the canal changes and assumes different dimensions.

In this case study we will take an example section with the following characteristics:

Top width	17.5 m
Top width (quays included)	24 m
Full Supply Level (FSL) width	13.8 m

Two types of structures will be assumed:

- Scheme 1: suspension cable
- Scheme 2: steel truss

Construction assumptions

For the sizing of the proposed structures, the following solar panel will be taken as reference a 400W monocrystalline PV solar panel with the below main mechanical features:

Dimensions	1754 x 1096 x 30 mm
Weight	21.0 kg

The structure must not only withstand the load of the PV panels, but also the forces resulting from atmospheric phenomena such as wind, rain and snow. Snow in particular poses a major risk, as it can easily accumulate above the panels, increasing the weight that the support structure must bear. For the dimensioning of support structures, therefore, the maximum foreseeable snow load is an important variable to consider. Wind stress has not been considered in the present case study, because it is likely that the aerodynamic force exerted by the wind will be less than the maximum snow load.

Scheme 1: suspension cable

A suspended cable structure was assumed, represented in the elaboration in figure 7.

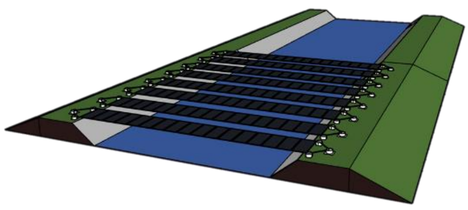

Figure 7. Conceptual representation of a suspension cable structure on CER

The term string is used to identify a single panel support section. As an example, eight (no.8) strings are shown in the section above.

So, assuming a layout of 8 strings, we performed the following calculations:

Number of panels for string	15 pc
Length occupied by panels per string	16.4 m
Width occupied by panels per string	1.8 m
Area occupied by panels per string	28.8 m2
Weight of the panels per string	315 kg
Power per string	6 kWp
Number of strings per section	8 string
Empty space between strings	1.5 m
Empty space between section of strings	3.5 m

Using the layout assumption introduced above, it is possible to carry out an initial dimensioning of the loads involved to size the materials required and evaluate costs. This cost contains the cost of the material for building the structure, labour and the necessary rental equipment. It does not include the cost of the panels, the cost of the inverters and the cost of the electrical service material for making the connections. This value will be set at 1.000 €/kWp and will include the cost of the electrical material, panels, inverters and installation. Assuming now the construction of a 1 MW pilot plant, we can calculate:

PV plant peak power	1 MW
Numer of strings	167 string
Length of the canal occupied	570 m
Concrete structures	112.425 €
Steel tubolars	9.100 €
Linkage and joints	86.250 €
Steel cables	62.100 €
Labour for structures only	75.000 €
Equipment rental	71.111 €
PV plant	1.000.000 €

The total estimated cost of the canal-top solar plant is about 1.415.986 €, in scheme 1 configuration. The suspension cable structure cost is 415.986 €, representing about the 30 % of the total cost.

Suspension cable structure	415.986 €	30 %
PV plant	1.000.000 €	70 %
Total cost	1.415 €/kWp	100 %

Scheme 2: steel truss

The structure, as opposed to 'suspension cable' technology, consists of steel beams transverse to the canal, placed on reinforced concrete plinths cast on the quays.

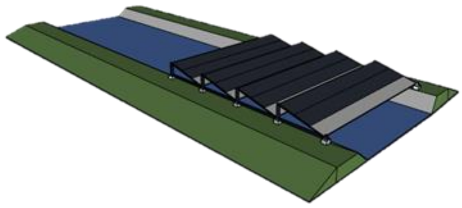

Figure 8. Representation of a steel truss structure on CER

Four (no.4) strings are shown in the rendering in figure 8. It should be noted that each string may contain up to three rows of panels with the long side agreeing with the section of the channel, or two rows if the panels are arranged in the opposite direction. It is also specified that each string must necessarily include an empty, unused area, since it is affected by shading from the neighboring string. This configuration, in relation to the dimensions of the canal section under consideration, allows us to calculate the following values:

Number of panels for string	30 pc
Length occupied by panels per string	17.5 m
Width occupied by panels per string	3.2 m
Area occupied by panels per string	57.7 m2
Weight of the panels per string	630 kg
Power per string	12 kWp
Number of strings per section	6 string
Empty space between strings	0 m
Empty space between section of strings	4 m

The structure was dimensioned considering the weight of the panels and the weight of the expected snow load. The material assumed for the construction consists of commercial beams and carpentry of different sizes. As carried out for scheme 1 hypothesis, we will use as a reference cost for the construction of the photovoltaic plant 1.000 €/kWp.

PV plant peak power	1 MW
Numer of strings	84 string
Length of the canal occupied	400 m
Concrete structures	37.921 €
Steel tubolars	499.230 €
Linkage and joints	9.166 €
Labour for structures only	46.666 €
Equipment rental	18.229 €
PV plant	1.000.000 €

The total estimated cost of the canal-top solar plant is about 1.611.212 €, in scheme 2 configuration. Following our calculations, the cost of the structure rises in this scheme representing about the 38 % of the total cost.

Suspension cable structure	611.212 €	38 %
PV plant	1.000.000 €	62 %
Total cost	1.611 €/kWp	100 %

Impacts on mantainance

The installation of solar panels on the canal is certainly a source of concern for the operating entity in charge of maintaining the canal. These entities must always have access to all portions of the canal to ensure that the primary mission of water delivery is accomplished.

The CER, like all canals, is likely to be subject to the following inspection operations: visual inspections and physical inspections. It is also subjected of corrective operations, such as structural repair (subsidence, lining cracks. bank erosion), cleaning (sediment removal, removal of animal burrows, removal of vegetation) and cleaning and restoration of flow control structures. Lattice foundations placed on canal banks would block access to large mobile equipment for canal repair, bank maintenance and weed removal. A specific example found in the literature concerns Arizona's canal network [9]. The case concerns a situation in which canal lining and banks were repaired following the detection of seepage. Specifically, a critical, time-consuming, and costly repair was conducted because the canal lining and embankment failed near the pumping plant, causing a prolonged interruption in water transport. During this repair, the aerial inspection from the helicopter noticed another failure of the lining and the repair area was extended. The covering of the canal surface and lining would prevent this type of inspection and observation of the canal lining. However, the canal in question was very large, justifying an aerial inspection. In the case of smaller canals, the inspection is normally conducted from the ground and would therefore be less easy due to the structures present, but still feasible.

Of the above operations, essentially all mechanized operations operating directly within the occupied area would be prevented, unless the plant is temporarily dismantled and set aside. Non-mechanized operations would also be substantially impeded, to a greater or lesser extent depending on the height of the panels from the ground and the distance between the supporting structures. Maintenance aspects and the impact of the top canal plant on them are summarized in table 5. Positive aspects are identified by the (+) symbol, negative by (-).

TABLE 5. Mantainance aspects

Type of intervention	**Description**	**Impacts of "Canalvoltaico"**
Structural repair	Necessary to prevent the sealing of the canal section affected by: - Infiltration and cracks - Breakdowns - Erosion	It may be necessary to temporarily remove the implant in order to carry out the repair easily (-)
		Mitigation of atmospheric damage (+)
Sediment removal	To remove the deposition of material in the channel bed (debris, dust, mud and organic material) that would otherwise reduce the useful flow of the channel.	It is necessary to temporarily remove the system for cleaning purposes (-)
		As an alternative to mechanised removal, pumping systems can be used.
		Mitigation of the accumulation of algae and other organic plant material (+)
Removal of vegetation from the canal	Where there is an accumulation of material (canal bed, cracks in the banks), weeds may proliferate. Periodic removal is necessary to promote water flow and prevent excessive degradation of the canal lining.	Cleaning by mechanised means is not possible, unless the system is dismantled. Manual cleaning with special tools is therefore necessary (-)
		Mitigation of the accumulation of algae and other organic plant material (+)
Removal of vegetation from the quays	To allow access to the canal, vegetation must be removed from the banks.	Care must be taken not to damage the installation. If necessary, temporarily install protective barriers to allow removal by mechanised means.
Removal of animal burrows	They can obstruct channel flow or promote structural degradation.	The plant may favour the settlement of animals underneath its structure (-)
		Removing the burrows will be less easy (-)
Cleaning and restoration of flow control structures	Pumping systems and mobile barriers must be maintained periodically, by removing debris, ensuring their tightness and mobility, and acting on malfunctions if necessary.	Not interested

Safety aspects

During the design phase, all safety aspects must be included, concerning both the construction and commissioning phase of the structures, and the production and service life phase of the plants. As far as the construction phase of the plants and structures is concerned, it will be necessary to strictly adhere to the Italian Consolidated Safety at Work Act (Dgls 81/2008) and to draw up, as required by law, an operational safety plan (so-called POS).

It is not within the scope of this study to carry out a risk assessment analysis. However, we can assume that this analysis, carried out in line with an analysis for a normal photovoltaic installation, will have to consider some additional factors, such as the risk of drowning and the presence of suspended loads. Regarding the production phase of the installation, the safety risks associated with solarization of the water basin will have to be assessed. For example, the structure could make it difficult to escape in the event of a fall into the water, it could be used to pass from one side of the canal to the other, causing risky situations. Another factor to be taken into consideration is the possibility of crimes, such as the theft of paneling, equipment and electrical wiring. In Italy, unfortunately, the phenomenon is constantly growing, although there are no official estimates to confirm this.

For the different reasons outlined above, a perimeter fence around the solar canal sections should be envisaged at the design stage. The fence should be built according to existing regulations, i.e., without being planted in kerns or walls, with a maximum height of 2 meters and the mesh placed 25 cm above the ground to allow the passage of small fauna. A fence would also benefit the already existing infrastructure in terms of safety and prevention. Now, in fact, the CER is not fenced. From our direct calculations, the total cost to fence 1 MW of canal-top solar plant is about 13.200 €.

Water saving

Starting from the regional climatic conditions [12] the annual evaporation potential of an uncovered water surface was estimated using the well-known Visentini formula [13] [14].

$$E_a = \sum_{m=1}^{12} b(t_m)^{1.5} = 1.621\ mm$$

Where:

$m = month\ index\ (1-12)$

$E_a = annual\ evaporation\ [mm]$

$b = empirical\ coefficient\ (2.25\ Romita, 1953)$

$t_m = average\ temperature\ of\ month\ m\ [°C]$

We evaluated the surface area of the CER covered by canal-top plant, both in scheme 1 and scheme 2.

Area occupied by panels	m2/string		
Scheme 1	28.8	167 strings	4.810 m2
Scheme 2	57.7	84 strings	4.846 m2

Assuming an average value of 4.830 m2, is possible to estimate the amount of water saved annually, by a 1 MW canal-top plant.

$$E_a(CER) = 4.830\ x\ 1{,}621 = 7.829\ m3/year$$

Visentini's formula, as shown in this study [15], may overestimate the total evaporation (even more than 50%). For the purpose of this paper, the value obtained above is qualitatively sufficient. If a solarization project of the CER is to be realized, a more in-depth analysis with measurements using evaporimeters is required to confirm the estimates and equations used. Evaporation, indeed, is influenced by multiple factors:

An increase of:	**brings to a/an**:
Wind speed and turbolence	Increase evaporation
Relative atmospheric humidity	Decrease evaporation
Max. absolute atm. humidity	Decrease evaporation
Temperature	Increase evaporation
Irradiance	Increase evaporation

So, given the high variability of the climatic conditions along the CER, as well as the countless plant configurations, further investigations would be necessary to establish with certainty both the evaporation of water from the various sections of the CER, and the annual water savings from the installation of canal-top systems.

Further relevant aspects

As a rule, the construction of plants must pursue the objective of minimal impact on the territory, both visually and environmentally, resorting not only to the best technologies available, but also to appropriate mitigation works. Mitigation works generally refer to naturalistic solutions, such as hedges [16]. In the case of a canal-top plant, the placement of mitigation works would be complex due to the very nature of the infrastructure and is therefore a solution to be ruled out. The design of the structures must therefore consider the visual impact without the possibility of adjacent natural mitigation structures. The CER, however, mostly passes through agricultural areas, many of which contain tree crops that themselves serve as mitigation. Moreover, the CER itself has its own visual and landscape impact that cannot be eliminated. Solarization of the canal would not significantly aggravate this impact.

With regard to the land fauna, the main users of the canal are birds, such as ducks, and rodents, especially nutrias. The layout, sized with sufficient space between the strings, allows animals to access the canal without hindrance. Even if a perimeter fence is installed, it must provide the appropriate spaces on the ground for the passage of small fauna, as per regulations. No criticalities for the animals involved are therefore expected.

Figure 9. CER section near Cesena (Forlì-Cesena)

IV. RESULTS AND DISCUSSION

“Canalvoltaico”, canal-top solar, is a recent technology that is still being studied. A general review of the literature and the plants currently in operation around the world, and an assessment of their size and construction characteristics revealed a lot of useful information to start approaching the subject in our national context as well. Most of the applications are in India. Unfortunately, not much information is available. Our research revealed that no useful technical scientific literature has been produced on the plants already operating in the state. Projects have recently been launched in the USA. The projects are in the start-up phase and even here, no useful experimental data are yet available. In addition, due to the inherent innovative nature of these projects, there is currently no information available on the life cycle of the facilities and the degradation of the equipment.

Our research points out that the structures used are basically of two types: tensile structures/suspension cables structure and steel truss structures (with beams). As a result of our calculations, the cable and guyed structures allow for a significant reduction in structure costs (15-20%). In any case, the costs of the structures are not negligible: they account for between 25% and 45% of the total cost.

Below a summary table with the values calculated in the CER case study, for 1 MW plant.

TABLE 6. Summary table

	Suspension cable	Steel truss
PV plant nominal power	1 MWp	1 MWp
Length of the canal occupied	570 m	400 m
Total cost estimated	1.415.986 €	1.611.212 €
of which for the structure	*415.686 €*	*611.212 €*

Truss structures are more massive and more expensive. The amount of material required is greater and the weight of the system itself is not negligible. It should be noted that the design proposals in the following paper do not constitute a feasibility engineering study. The capacity of the embankments and the structural characteristics of the canal must be carefully evaluated when starting similar projects.

The solarization and consequent covering of water courses generates a considerable water benefit, due to reduction of water evaporation from canals, estimated to 7.829 m3/year per MW. When applied in densely populated or highly agriculturally productive regions, canal-top solar results in significant soil savings. Compared to utility scale ground mounted PV plant, the land saving of 1 MW canal-top plant is between 2.5 and 3 hectares.

This study highlights also some critical issues:

- Relatively high investment costs when compared to other types of photovoltaic systems.

- Difficulties in maintenance operations. The main function of the CER is to supply water to the agricultural sector. Such a system could lead to an increase in operating costs. We could not estimate this additional cost.

- The floods that hit our region hard in May 2023 also highlighted the need for adequate flood protection. Extreme events (as snow, floods, hail, etc.) which are unfortunately becoming increasingly frequent, can threaten the stability of infrastructure and menace investments made.

“Canalvoltaico” on the CER would certainly be easier in sections with a smaller width and flow rate, such as those in the last section of the infrastructure. In these sections, (figure 9) installation would probably be easier and less expensive due to the presence of railings along the entire edge of the canal. In addition, the panels would be elevated above the ground, reducing the possibility of flood damage.

Also in this case, all the considerations made in the previous paragraphs regarding maintenance and other relevant aspects apply. This configuration should be the subject of further analysis.

IV. CONCLUSION

Photovoltaics is certainly one of the most promising renewable energy sources to decarbonize the energy sector. In order to safeguard land consumption and exploit possible co-benefits, canal-top photovoltaics, as well as agrivoltaics, proves to be an interesting technology where much research and study work still needs to be done.

This article has presented a review of the world's first canal-top solar plants, shedding light on its potential as a viable renewable energy solution. Building upon this review, a preliminary feasibility study was conducted specifically for canal-top solar plants in Italy (CER case study), with a focus on identifying the associated costs, benefits, and criticalities. As mentioned above, this report represents the first feasibility study for canal-top solar technology carried out in Italy.

The findings of this study provide valuable insights for the scientific community and offer practical guidance as a starting point engineers and researchers involved in the renewable energy sector.

By highlighting the costs, benefits, and criticalities associated with this innovative renewable energy solution, this research aims to inspire and guide further advancements in canal-top solar technology, ultimately contributing to a more sustainable and greener future.

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