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Article

"Canalvoltaico" in Emilia-Romagna, Italy: Assessing Technical, Economic, and Environmental Feasibility of Suspended Photovoltaic Panels over Water Canals

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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, which raises the issue 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 feasible application in the Italian region "Emilia-Romagna" is discussed, evaluating two potential construction designs. The primary aim is to establish a capital expenditure cost framework, offering reference values currently lacking in the extant literature and industry studies pertaining to Italy. Moreover, the study addresses additional key factors, including water savings, maintenance considerations, and safety implications.

Keywords: renewable energy; photovoltaic; solar energy; water canals; Canal-Top solar; sustainability; Canalvoltaico

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1. 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]. In 2022, Italy achieved a record photovoltaic production of over 28 TWh, marking a 12.3% increase compared to the previous year [2]. In accordance with the major European scenarios, photovoltaic production is projected to surpass 35 TWh by 2030. The more "optimistic" scenarios even forecast substantially higher levels of production [3,4].

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 [5].

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. Currently, there is a noticeable lack of detailed cost analyses for canal-top solar installations. This deficiency is emphasized by a recent systematic review that examined the widespread adoption of water-based photovoltaic (WPV) systems globally. The review reveals that clear cost analyses for Canal-Top installations are currently lacking [6].

Indeed, at the time of publication of this article, based on our best research efforts, we have not identified any comprehensive studies and cost analyses regarding the application of Canal-Top technology in Europe, specifically in Italy. No analysis has been found that highlights the required investments, particularly in comparison to conventional photovoltaics, or addresses implications on relevant aspects such as maintenance, safety, and conflicts with other water users. While detailed studies have been conducted on evapotranspiration over panels above water mirrors and panel degradation, there is a notable absence of an inclusive applied study. Thus far, no comprehensive study has been identified that encompasses all these aspects.

The objective of this study is to provide an initial comprehensive analysis of the potential application of this technology in Italy. The study focuses on the investment cost analysis of two possible construction design types: suspended-cable and steel-truss designs.

We hope the paper lays the foundations for further in-depth studies contributing to scientific and industrial research on this technology.

2. Materials and Methods

A comprehensive literature review was conducted to examine the 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.

The Emilia-Romagna region was chosen for the case study as it is a region characterized by high industrial, agricultural, and housing density at the same time [7]. On a local level, this results in very high energy consumption and a lack of large spaces where photovoltaic systems can be placed. In addition, climate change is posing water supply risks for land uses. The Emilia-Romagna region faces a high water risk, which may exacerbate in the future [8]. These characteristics are common to other regions in northern Italy, such as Piedmont, Lombardy, and Veneto, as well as to other European regions similar in terms of economic and climate, such as Spain, France, and Germany. Furthermore, Emilia-Romagna was chosen for the territorial presence of the University of Bologna, making it easier for researchers to collect data.

A load analysis, considering static forces, was performed to accurately size the supporting components. Starting from the environmental loads and optimal panel orientation angles, the forces acting on the support structures were calculated. The analysis allowed the sizing of pier dimensions along the canal quays, the dimensions of support beams, and the thickness of metal cables. Subsequently, tension members and joints were evaluated, along with the necessary metallic hardware for securing the panels to the supports.

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. The values used in the cost analysis were sourced from market data and by consulting local supplier companies.

Water saving through the reduction of evaporation was estimated through Visentini equations. Various aspects such as maintenance impacts, safety risks, and ecological considerations were qualitatively examined.

3. Results

3.1. A Review of Canal-Top Solar Plants 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.

Figure 1. Maps of Canal-Top solar plants in the world (our elaboration).

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

(i) Steel-truss structures, transverse to the course of the canal, with reinforced concrete supports on the quays;

(ii) 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 the "Sardar Sarovar Solar Project", from the name of the dam from which a massive canal system, stretching 71,748 km into the region, originates [9–11]. The main characteristics of the structure have been reported in Table 1. Regarding this project, technical information is available concerning the specifications of the panels, their positioning, potential shading, and the use of reflectors to enhance their efficiency. Costs are also detailed and categorized according to major components [12], except the steel-truss-structure cost. Costs for solar panels and electrical materials are indicated as EUR 1.18 per Watt. For this project, the degradation rate of PV modules was also studied, revealing an increase compared to ground-mounted installations [13]. The amount of water saved was estimated to be around 1.83 cubic meters on a squared meter of canal covered by panel [14].

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" (Table 2) to set up pilot plants totaling 20 MW [15,16]. The PV installed on the Punjab canals utilize a different technology than the others Gujarat projects, using cables and guy wires (suspension cable technology).

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

Yamunua Canal in the Dehradun region represents the world's largest tensile structure for supporting photovoltaic panels (the width of the canal reaches 37 m) [17]. For both the Yamunua project and the Pilot-cum-Demonstration Project, at the time of our research, we did not find any additional information pertinent to the development of our case study.

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) [18]. 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. The planned structure is of the steel truss type, with reinforced concrete foundations.

The estimated costs for the construction of the 1 MWp 'pilot' section is USD 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 7400 cubic meters (about three 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. The study conducted by the Bureau of Reclamation is currently the most comprehensive document available and has been instrumental in shaping the development of our case study.

In California, 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 [19]. No technical information about size and structure are available. From the conceptual rendering available from the TID website, the planned structure is of the steel-truss type, with reinforced concrete foundations [20].

TID started the project in the autumn of 2022. Full completion of the project is expected by the end of 2023. No further information was available at the time of composing this document.

3.2. 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) (Figure 2). This analysis requires consideration of construction assumptions and the associated costs and maintenance and safety considerations.

The CER is one of the most important hydraulic works in Italy [21]. By deriving water from the Po River, it ensures the supply of water to four provinces, starting in the province of Ferrara and ending in the province of Rimini, with a total length of 135 km [22]. Its flow rate progressively decreases along the route, decreasing from 60 m^3/s to 6 m^3/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 of 17.5 m, top width (quays included) of 24 m, and full supply level (FSL) width of 13.8 m. These dimensions of the canal can be found, for example, in the section of the CER at Barisano, in the municipality of Forlì (FC).

Two types of structures will be assumed: (i) Scheme 1—suspension cable; (ii) Scheme 2—steel truss.

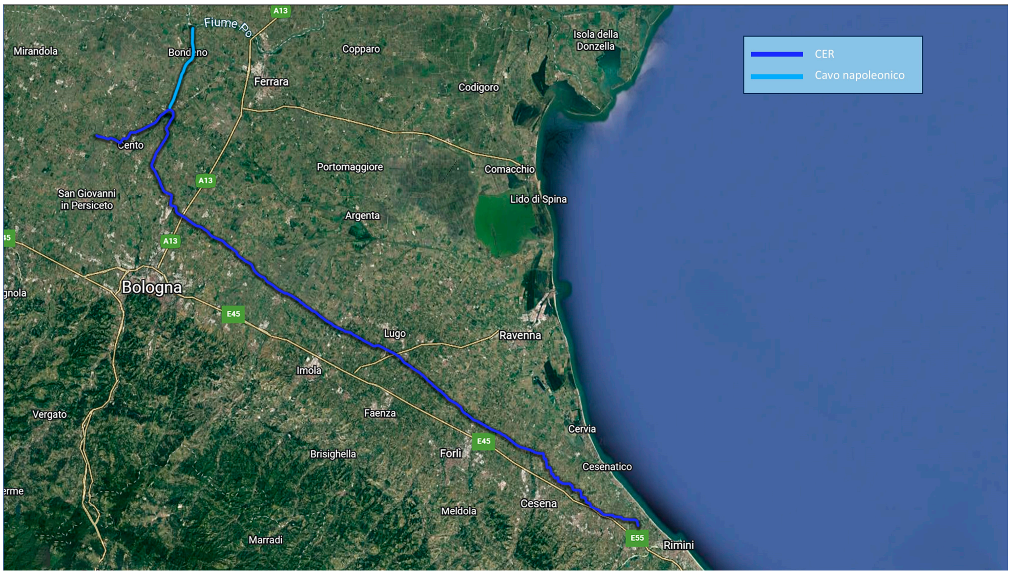

Figure 2. Geographical map (Google Earth) with the route of the CER, which is the blue line (our elaboration).

3.2.1. Construction Assumptions

According to the sizing of the proposed structures, a 400 W monocrystalline PV solar panel was taken as the reference. The panel measured 12 × 4 × 7 in length and weighed 13 kg.

The assumed solar panel measured 1754 × 1096 × 30 mm in length and weighed 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.

In 2012, the Emilia-Romagna region experienced the most significant snowfall of the past century. Some areas of the plain were covered by nearly two meters of fresh snow [23].

In accordance with the Technical Standards for Constructions, the load capacity of the structure should be approximately 100 kg/m^2 [24]. This value can be compared to the extreme event that occurred in 2012, assuming an average fresh snow density of 50 kg/m^3.

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.

To avoid any damage from the overflow of the canal or floods caused by rainfall, the photovoltaic panels must be elevated above the canal banks by at least thirty centimeters. The structure will have to be as high as the level reached in the event of a flood. Finally, it is not recommended to install such a system in high-risk areas, such as those heavily affected by the flooding in Emilia-Romagna in May 2023.

The costs of the photovoltaic system (excluding structure) were provided by a local photovoltaic installer, while the costs of the structure were estimated through contacts with two local builders.

3.2.2. Scheme 1: Suspension Cable

A suspended cable structure was assumed, represented in the elaboration in Figure 3. 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.

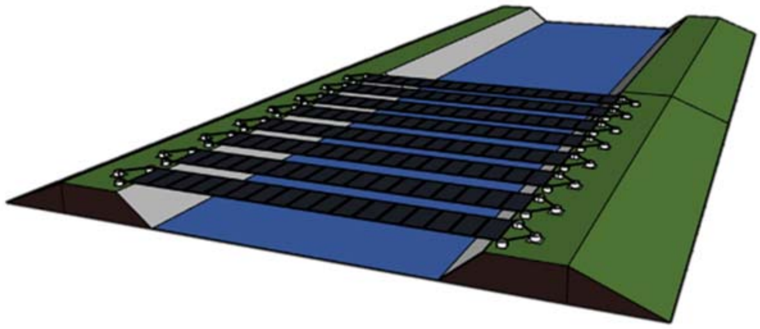

Figure 3. Conceptual representation of a suspension cable structure on CER (our elaboration).

So, assuming a layout of eight strings, we performed calculations which are reported in Table 3.

Table 3. Example of an eight-strings panel support.

Mechanical Features	Measure
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 m^2
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 assess the materials required and evaluate costs which are reported in Table 4. This cost contains the cost of the material for building the structure, labor, 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 EUR 1000/kWp and will include the cost of the electrical material, panels, inverters, and installation.

Table 4. Example of a 1 MW pilot plant construction according to the scheme 1.

Pilot Plant Features	Measure
PV plant peak power	1 MW
Number of strings	167 string
Length of the canal occupied	570 m
Concrete structures	EUR 112,425
Steel tubulars	EUR 9100
Linkage and joints	EUR 86,250
Steel cables	EUR 62,100
Labor for structures only	EUR 75,000
Equipment rental	EUR 71,111
PV plant	EUR 1,000,000

Assuming now the construction of a 1 MW pilot plant, with the features shown in Table 4 we could calculate the total estimated cost of the Canal-Top solar plant in the Scheme 1 configuration, which amounts to 1,415,986 € (1415 €/kWp). The suspension-cable-structure cost is EUR 415,986, representing about the 30% of the total cost.

3.2.3. 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.

Four (No. 4) strings are shown in the rendering in Figure 4. 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.

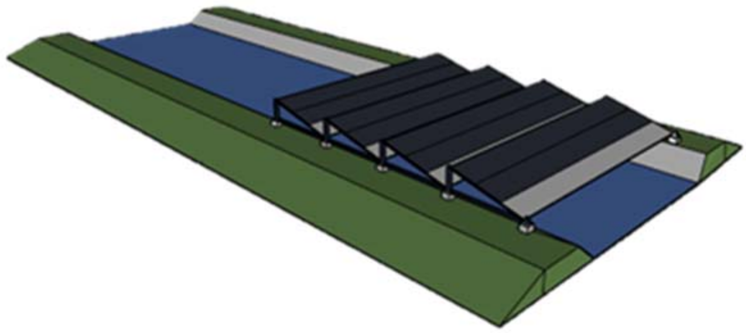

Figure 4. Conceptual representation of a steel-truss structure on CER (*our elaboration*).

This configuration, in relation to the dimensions of the canal section under consideration, allows us to calculate the values listed in Table 5.

Table 5. Example of a steel-truss structure panel support.

Mechanical Features	Measure
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 m^2
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 the Scheme 1 hypothesis, we will use this as a reference cost for the construction of the photovoltaic plant EUR 1.000/kWp, as reported in Table 6.

Table 6. Example of a 1 MW pilot-plant construction according to Scheme 2.

Pilot Plant Features	Measure
PV plant peak power	1 MW
Number of strings	84 string
Length of the canal occupied	400 m
Concrete structures	37,921 €
Steel tubulars	499,230 €
Linkage and joints	9166 €
Labor 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 EUR 1,611,212, in the Scheme 2 configuration. Following our calculations, the cost of the structure rises in this scheme representing about the 38% of the total cost.

3.2.4. Impacts on Maintenance

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 to corrective operations, such as structural repair (subsidence, lining cracks, and bank erosion), cleaning (sediment removal, removal of animal burrows, and 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 in 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 7. Positive aspects are identified using the (+) symbol and negative using (−).

Table 7. 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 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 mechanized 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 and cracks in the banks), weeds may proliferate. Periodic removal is necessary to promote water flow and prevent excessive degradation of the canal lining.	Cleaning via mechanized means is not possible unless the system is dismantled. Manual cleaning using special tools is, therefore, necessary (−).
		Mitigation of the accumulation of algae and other organic plant material (+)

Table 7. *Cont.*

Type of Intervention	Description	Impacts of "Canalvoltaico"
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 via mechanized means.
Removal of animal burrows	They can obstruct channel flow or promote structural degradation.	The plant may favor 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

3.2.5. 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 m, 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 EUR 13,200.

3.2.6. Photovoltaic Production

The yearly photovoltaic production of the 1 MWp plant has been calculated through the Photovoltaic Geographical Information System (PVGIS) provided by the European Commission Joint Research Centre [25].

The simulation parameters were set as follows:

- The azimuth angle (orientation) of the panels was set at 45° southeast, as this orientation is preponderant throughout the canal route;
- The tilt angle (inclination) of the panels was set at 30°, the optimum angle for the productivity of the system, as suggested by the tool itself;
- The location was set as Lat/Lon 44.421, 11.858, in the locality of Barisano, in the municipality of Forlì;
- The system loss was set as 14%, the standard reference, as suggested from the tool itself;
- Other settings as per tool default.

From the above hypothesis, the tool evaluated a yearly photovoltaic electricity production of 1.248 MWh.

Given an electricity market price of EUR 125/MWh for the fourth quarter of 2023 [26], when the article was revised, producible electricity would have a value of EUR 156,000.

The productivity of the photovoltaic panels may be even higher, thanks to the cooling effect of the canal. A recent study, developed in Cagliari Italy, showed a possible increase of 1.2% in production [27]. However, as the evidence of this phenomenon is limited and the increase is marginal, for simplicity's sake, this effect has not been considered in the calculation of the Net Present Value.

3.2.7. Water Saving

Starting from the regional climatic conditions, available on the European JRC's PVGIS platform [25], the annual evaporation potential of an uncovered water surface was estimated using the well-known Visentini formula [28].

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

where

m = month index $(1 - 12)$
E_a = annual evaporation [mm]
b = empirical coefficient (2.25 Romita, 1953)
t_m = averag etemperature of month m [°C]

We evaluated the surface area of the CER covered by Canal-Top plant, both in Scheme 1 and Scheme 2 as shown in Table 8.

Table 8. Area occupied by panels.

Scheme	m^2/String	Number of Strings	Surface Area (m^2)
Scheme 1	28.8	167	4.810 m^2
Scheme 2	57.7	84	4.846 m^2

Assuming an average value of 4.830 m^2, is possible to estimate the amount of water saved annually by using a 1 MW Canal-Top plant:

$$E_a(CER) = 4.830 \times 1.621 = 7.829 \frac{\text{m}^3}{\text{year}}.$$

Visentini's formula, as shown in this study [29], may overestimate the total evaporation (even more than 50%).

The Visentini method relies on the utilization of an empirical formula, whereas more complex methodologies, such as the Penman model, have the capability to account for multiple factors in their calculations. The Penman model considers a range of variables to provide a comprehensive estimation of evapotranspiration, encompassing factors like solar radiation, air temperature, wind speed, and atmospheric pressure [30].

Effectively utilizing the Penman–Weidth model requires careful consideration of these input parameters to ensure an accurate depiction of the environmental conditions influencing the evapotranspiration process. Notably, the canal under examination deviates from a typical open water body. Considering the presence of numerous obstacles and structures along the canal, obtaining precise results, especially in incorporating a wind function, poses considerable challenges.

Simplifying, we summarized the most significant effects on evapotranspiration in Table 9.

Table 9. Factors influencing evaporation.

Climatic Parameters	Resulting Effect
Increased wind speed and turbulence	Increased evaporation
Increased relative atmospheric humidity	Decreased evaporation
Increased max. absolute atm. humidity	Decreased evaporation
Increased temperature	Increased evaporation
Increased irradiance	Increased evaporation

In relation to the points mentioned above and the purpose of this paper, the value obtained through Visentini equation 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.

So, given the high variability of the climatic conditions along the CER, as well as the countless plant configurations, further "on-site" 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.

To attempt to quantify the positive impact of water savings resulting from canal coverage, we need to consider that the Reclamation and Irrigation Consortium serves an irrigated surface area of approximately 158,000 hectares through canal systems. Estimates from the Emilia-Romagna Reclamation Consortium indicate an increase in Gross Marketable Production (PLV) ranging from EUR 0.35 to 1.00 per cubic meter, depending on water availability during the year [21]. Given the persistence of increasingly drought-prone years in Italy [31,32], we may evaluate the value at EUR 1 per cubic meter. Economically, we could evaluate the annual saving, for 1 MW canal top plant, as below:

$$S_a(CER) = E_a \times 1 = 7.829\text{ €/year}.$$

3.2.8. Other Ecological Aspects

In addition to achievable water savings, Canal-Top photovoltaic systems offer multiple ecological considerations, both positive and negative. The utilization of water channels for energy production constitutes a significant advantage in land-use optimization, compared to conventional ground-mounted PV plants. This approach to agrivoltaic technologies, preserves agricultural land from that potential impact [33–35]. Ground-mounted photovoltaic installations can occupy an area ranging from 10,000 square meters to well over 40,000 square meters, depending on the configuration (fixed, single-axis, dual-axis, etc.) [36].

The ecological impact in terms of water quality in canal top photovoltaic systems has predominantly been explored theoretically, with a dearth of current studies on operational installations based on our extensive research. An intriguing recent study, conducted in the Netherlands, implemented weekly monitoring registering key water quality indicators, including total nitrogen (TN), total phosphorus (TP), chlorophyll-a (a measure of total phytoplankton abundance), and cyanobacterial chlorophyll (a measure of potentially toxic cyanobacterial abundance, cyano-Chl) [37]. The study reported no significant differences in relevant water quality parameters and water temperature. Nevertheless, aquatic plants that have already been established exhibit a threefold reduction in biomass accumulation. A camera trap was installed to study birds' behavior. Currently, there is a lack of concrete information regarding the effects on aquatic animals.

3.2.9. Conflict with Other Water Uses

Irrigation canals are used primarily for irrigating fields: water is drawn through a hose, which feeds pumping units (diesel or electric) connected to the irrigation system. Given the necessary spacing between photovoltaic panels and the canal surface, access to water for additional irrigation purposes is, thus, guaranteed.

A secondary purpose of water channels, but of utmost importance should climate events worsen in the future, is the possibility of draining surface water from precipitation.

Again, the structure of the system should not interfere with this function of the canal, given the distance between the supports and the width of the piles themselves.

3.2.10. 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 [38]. 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.

3.2.11. Net Present Value

The Net Present Value (NPV) of the systems are indicated in the Table 10. The NPV was calculated considering the previously calculated investment cost for both types of structures (Sections 3.2.2 and 3.2.3) and the positive cash flows from the sale of electricity (EUR 156,000/year, as in Section 3.2.5) and water savings from evaporation (EUR 7800/year, as in Section 3.2.6). The increase in the canal maintenance costs was not considered. The increase in the degradation rate of panels was not considered. The discount rate was set equal to Italy's government bonds (5% in the fourth quarter of 2023) [39]. A cautionary life-span for the plant of 15 years has been considered. Disposal costs have been neglected, as they are of marginal impact.

Table 10. Economic performance calculations (NPV and Simple Payback).

Economic Parameter	Suspension Cable	Steel Truss
CAPEX (EUR)	1,415,000	1,611,000
OPEX EUR/year)	164,000	164,000
Simple Payback (years)	8.6	9.8
Net Present Value (EUR) (15 years)	1,045,000	850,000

4. Discussion

"Canalvoltaico", Canal-Top solar system, 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 has revealed that there is a limited amount of useful technical–scientific literature available on the plants that are already operational. Projects have recently been launched in the USA. The projects are in the start-up phase; even here, no useful experimental data are yet available. In addition, owing to the inherent innovative nature of these projects, there is currently a lack of information available regarding the lifecycle of the facilities and the degradation of 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.

The values calculated in the CER case study for a 1 MW plant are reported in Table 11.

Table 11. Summary table.

Structures' Features	Suspension Cable	Steel Truss
PV plant nominal power	1 MWp	1 MWp
Length of the canal occupied	570 m	400 m
Total cost estimated	EUR 1,415,986	EUR 1,611,212
Cost estimated for the structure	EUR 415,686	EUR 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.

We did not conduct a Net Present Value (NPV) analysis of the investment because we believe it is necessary to initiate a pilot project for the precise quantification of maintenance costs. This includes operational impact on canal operations as well as photovoltaic system degradation. That being said, taking into account an average electricity selling cost of EUR 0.15/kWh and assuming that routine maintenance operations for the solar installation incur a relatively low cost of EUR 50/kWp per year, the payback period for a canal photovoltaic system would significantly exceed 10 years. So, for a proper evaluation of the investment and the time of return, we cannot exclude the co-benefits of CanalTop technology from the analysis, particularly the savings in valuable land and irrigation water.

With regard to these two aspects, the study has highlighted that 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 m^3/year per MW in the Emilia-Romagna region). When applied in densely populated or highly agriculturally productive regions, Canal-Top solar results in significant soil savings. Compared to a utility-scale, ground-mounted PV plant, the land saving of 1 MW Canal-Top plant is between 2.5 and 3 hectares.

So, the study has highlighted the following critical issues:

(i) Relatively high investment costs when compared to other types of photovoltaic systems. In economic plans that do not account for the co-benefits of photovoltaic technology, the results are 'negative' (with excessively long payback periods).
(ii) 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.
(iii) The floods that hit our region hard in May 2023 also highlighted the need for adequate flood protection. Extreme events (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, 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.

5. Conclusions

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, prove to be an interesting technology where much research and study work still needs to be done.

This article has presented a concise 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 for engineers and researchers involved in the renewable-energy sector.

From our perspective, given the high costs and potential challenges highlighted, it is currently not cost-effective, nor will it be in the near future, for companies and consortia to invest in canal photovoltaics. However, this may not hold true indefinitely, given the rapid evolution of energy landscapes and the critical nature of land and water resources. The reduction in costs associated with the purchase of solar panels, the optimization of facility costs, and the potential for economies of scale could, in the medium term, make this technology more economically attractive. This is especially true considering the ecological savings, both in terms of water and land conservation.

An interesting development could be the possibility of envisioning new channels with this technology and quantifying costs for channels already designed to be covered by solar panels.

It would be advisable, as well as highly interesting and scientifically significant, to invest in a similar pilot research project, possibly in the Emilia-Romagna region or in Italy as well. Through the implementation of a pilot plant, it would be possible to more accurately define investment costs by precisely capturing all expenditure items. Additionally, the pilot plant would enable the quantification of potential increases in maintenance costs, which could have a significant impact. Furthermore, it would allow for a thorough study and quantification of ecological aspects, primarily the savings attributed to water evaporation. A pilot implementation project should be conducted by consortia and canal management entities, in synergy with local research institutions.

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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