

Original Article

Investigation of Key Parameters Affecting the Performance and Feasibility of Canal-Top Solar Photovoltaic Systems

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Abstract - Nowadays, energy consumption is one of the key indicators used to measure the development of a country. Electricity consumption is one of the main sources of energy. The substantial rise in the electricity requirement and rapid diminution of fossil fuels, together with environmental matters during recent years, have led to the necessity of commissioning new green and efficient power plants. To address global challenges such as reducing CO₂ emissions and avoiding extreme climate change conditions, energy production using renewable energy sources is increasing rapidly all over the world. Solar energy is one of the most abundant sources of renewable energy. One of the main disadvantages of solar energy is the enormous amount of land required, as approximately 2.5 acres of land are required per MW of power production. Especially in a high population density country like India, installing a solar energy plant becomes problematic because land is used for solar plants instead of agricultural purposes. Further, there are a number of problems related to land, such as land acquisition, land development, land availability, and the time required for administrative clearance. The CTSPV (Canal-Top Solar Photovoltaic) system effectively addresses the major land requirement challenge by utilising existing canal infrastructure. Although CTSPV systems offer many benefits, including a 10% relative efficiency enhancement and a 60–90% reduction in evaporation rates that result in saving 9 million litres of water annually for every MW of power generated, regulated algae growth, and water-enabled cooling and cleaning, these advantages are significant. This paper investigates the key parameters affecting the performance, environmental impact, and economic feasibility of CTSPV systems through a comprehensive analysis of existing research studies.

Keywords - Canal-Top Solar Photovoltaic, Floating Photovoltaic, Renewable Energy, Solar Panel Efficiency, Water Conservation.

1. Introduction

The development of the national economy depends on many different factors, and one of the most significant is the volume of energy consumption [1]. Electricity is a significant portion of total energy usage. A 1% increase in economic growth (GDP) leads to a 1.310% increase in CO₂ emissions. Increased electricity consumption leads to higher CO₂ emissions. A 1% increase in electricity consumption in India results in a 1.8148% rise in CO₂ emissions [2]. After facing a serious setback from the pandemic, India has shown impressive growth, becoming the fifth-largest economy and is projected to be the third-largest by 2030. This growth performance has led the Prime Minister to set an ambitious target for India to become a developed country by 2047 [3]. However, to achieve this goal, a sustained annual GDP growth of 9-10% for the next 25 years means carbon emissions will again increase. Further, India set a net-zero carbon emission goal by 2070 [4]. Target 2047 and target 2070 are contradictory from a carbon emission point of view, and that's

why India must focus on renewable energy sources to achieve both goals. Based on data as of May 31, 2023, the total installed power generation capacity in India was 417,668 MW. Non-fossil fuels accounted for 179,322 MW, which is 43.0%. Renewable energy sources, including hydro power, produce 173619 MW or 41.4% of total installed capacity. Solar power contributes 67078 MW and representing 16.1% of total installed capacity [5]. To address the global climate change challenge, all over the world is now focusing on renewable energy sources, and that is the only solution for CO₂ emission reduction. Today, renewable energy reaches a 4448 GW capacity as of 2024, as shown in Figure 1. Annual growth is at 15.1% since 2010, which is remarkable, and it added 585 GW of renewable capacity in the last year. This expansion is mainly driven by solar energy because of technological improvements, cost reduction, and scalability [6, 7]. Still, this growth is less than to achieve the target of 2030. To achieve that target, the world needs to maintain an annual growth of 16.6%.



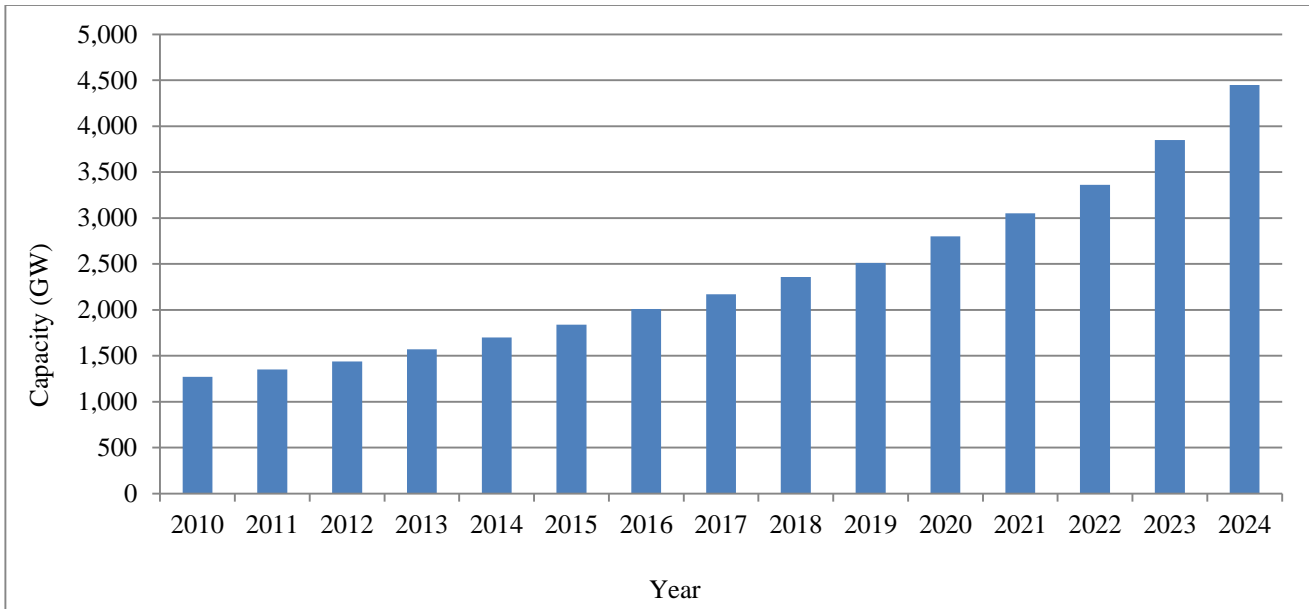


Fig. 1 Worldwide Renewable Energy Growth 2010 to 2024 [8].

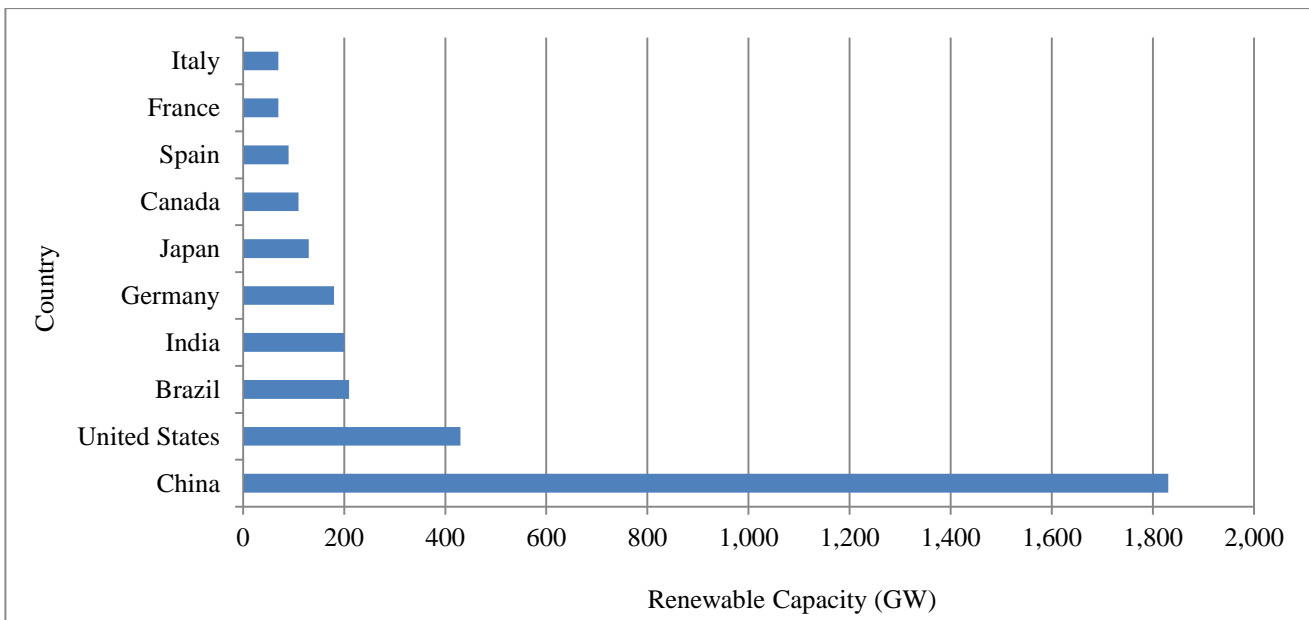


Fig. 2 The global renewable energy giant [11]

The challenge needs to accelerate renewable deployment and enhance international cooperation [6].

China is continually dominating global renewable energy deployment and contributing two-thirds of new renewable energy additions in 2024, followed by the USA, Brazil, India, etc., as shown in Figure 2. The G7 and G20 countries collectively installed 13.3% and 90.3% of renewable energy and contributed to clean energy investment [9]. India has emerged as a global leader in renewable energy deployment, demonstrating remarkable progress toward its ambitious climate goals. The country's renewable energy capacity has increased from 76.37 GW in March 2014 to approximately

244 GW by 2025, representing a more than three times increase in just over a decade, led by solar energy expansion, which increased nearly 50 times, as shown in Figure 3 [10].

Based on the mathematical model presented, India's solar photovoltaic (SPV) market is projected to reach saturation at 8.62×10^{11} W (0.862 TW) by 2062. The study reveals that India's share of global SPV production will increase from 5.2% in 2022 to 9.6% by 2050. According to the model's calculations, India is projected to reach 1.23×10^{11} W by 2030 [12]. It is clearly indicated that SPV is one of the main parts of RE in the future. The working principle and key advantages of the CTSPV system are illustrated in Figure 4.

Although several studies have investigated floating photovoltaic systems, cooling techniques, evaporation reduction, and land-based solar photovoltaic systems individually, a comprehensive review specifically focused on CTSPV systems is still limited. Existing studies mainly discuss isolated aspects such as water conservation, cooling effects, or power generation performance, while a detailed comparative analysis of technical, environmental, and economic parameters affecting CTSPV systems remains insufficient. Furthermore, limited literature is available addressing the combined impact of parameters such as canal orientation, evaporation reduction, dust penetration, algae growth, land conservation, degradation, and economic feasibility in a single framework. Therefore, this paper aims to systematically investigate the key parameters influencing the performance and feasibility of CTSPV systems and compare them with conventional land-based solar photovoltaic systems. The main contribution of this study is the comprehensive comparative assessment of CTSPV based on technical performance, environmental impact, water conservation capability, and economic feasibility.

The objectives of this review are: (1) to systematically review key parameters affecting CTSPV performance; (2) to compare CTSPV with land-based and floating PV systems; and (3) to identify research gaps and future directions.

2. Challenges in Existing Land-Based SPV Systems

Although SPV technology offers many benefits, several challenges remain in large-scale SPV installation. These include land acquisition, land development, land availability, and the time required for administrative clearance. One of the main challenges is the huge land area required that can be used for agricultural purposes. The current global PV land area of ground-mounted photovoltaic panels occupies approximately 3300 km² as of 2020 [13]. The most common land requirement for utility-scale solar photovoltaic installations is 5 acres per megawatt (MW) of installed capacity. This represents the standard range cited across multiple sources, particularly for installations in India and other developing markets [14]. Another major challenge is that the power produced decreases significantly with the rise in temperature of the panel above 25 °C. The maximum power produced will be reduced by 0.5% when the panel top surface temperature increases by 10 °C [15]. These two major challenges can be fulfilled in the CTSPV.

3. Novelty and Contribution

Although several review studies are available on floating photovoltaic systems, cooling techniques, and general solar photovoltaic technologies, a comprehensive review specifically focused on CTSPV systems is still limited. Existing studies mainly discuss isolated aspects such as evaporation reduction, cooling effects, or energy generation performance. However, a systematic comparative analysis

integrating technical, environmental, and economic parameters affecting CTSPV systems within a single framework is lacking in the literature. The novelty of the present review lies in the comprehensive assessment of CTSPV systems considering panel orientation, cooling effects, evaporation reduction, dust penetration, algae growth, degradation, land conservation, and economic feasibility together. Furthermore, a comparative evaluation between conventional land-based photovoltaic systems and CTSPV systems has been presented to identify key advantages, limitations, and future research directions.

4. Methodology of Literature Analysis

This study analyses published research articles on CTSPV systems collected from major scientific databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Relevant literature was selected based on keywords including CTSPV, floating photovoltaic systems, solar panel cooling, evaporation reduction, and land-saving solar technologies. The selected publications were analysed to identify key technical, environmental, and economic parameters influencing CTSPV performance. Particular emphasis was placed on parameters such as panel orientation, cooling effects, dust penetration, evaporation reduction, ecosystem impact, system degradation, and economic feasibility. Comparative evaluation of land-based solar photovoltaic (LSPV) systems and CTSPV systems was also carried out based on the findings reported in the literature to understand their relative advantages and limitations.

5. Parameters affected in the CTSPV

5.1. Direction of Panel

For an ideal condition, the sun is always in the longitudinal direction of the panel, but practically, that is not possible. Optimum tilt angle, as shown in Figure 5 for any location, depends on the latitude of the site, solar declination angle, and sunset hour angle for the tilted surface. So, the tilt angle is varied from location to location. The basic rule for optimum tilt angle is latitude $\pm 15^\circ$ [16]. For a fixed installation throughout the year, the optimum tilt angle for the Gujarat region would be approximately 18° to 23° [17]. The direction of solar panels in canal-top systems is fundamentally determined by the direction of the canal itself [18]. When the canal runs in a north-south direction, inter-array spacing between solar panels is required to maintain optimum tilt angle. Most canals in India run from north to south, making inter-array spacing the preferred orientation for canal-top solar projects as seen in Figure 6. For north-south-oriented canals, photovoltaic panels are positioned facing south. When the canal runs in an east-west direction, inter-array spacing can be avoided, and a single slope due south direction arrangement is used, as shown in Figure 7. Table 1 summarizes the different positions of the panel on the canal or experimental setup. Canal direction is not a controllable parameter, so canal direction and tilt angle are considered during site selection and from an investment point of view.

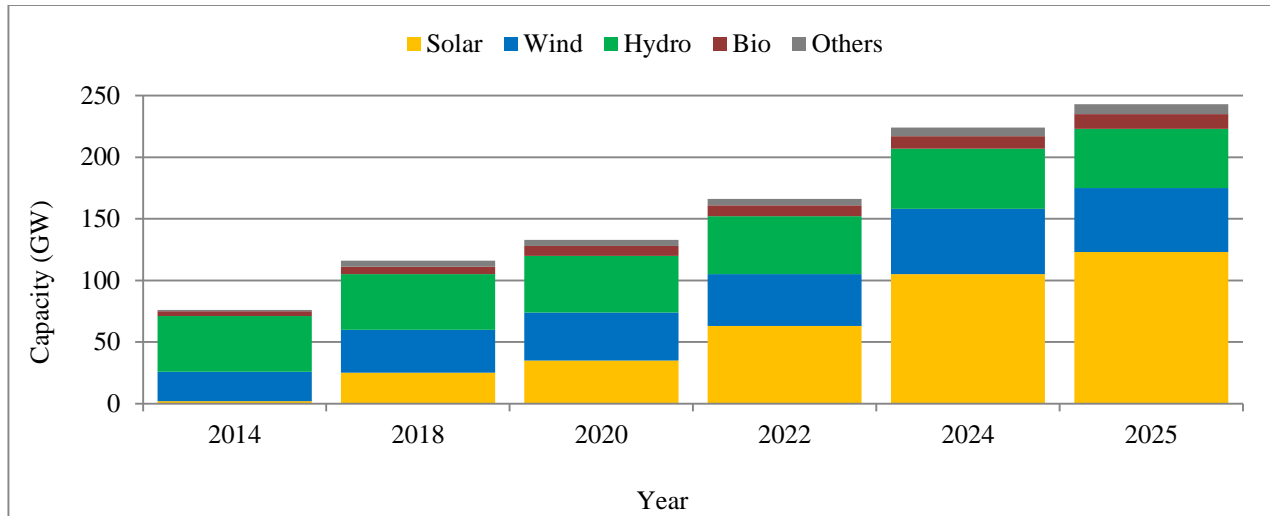


Fig. 3 India's renewable energy capacity growth and share of different sources led by solar energy expansion, which increased nearly 50 times [10].

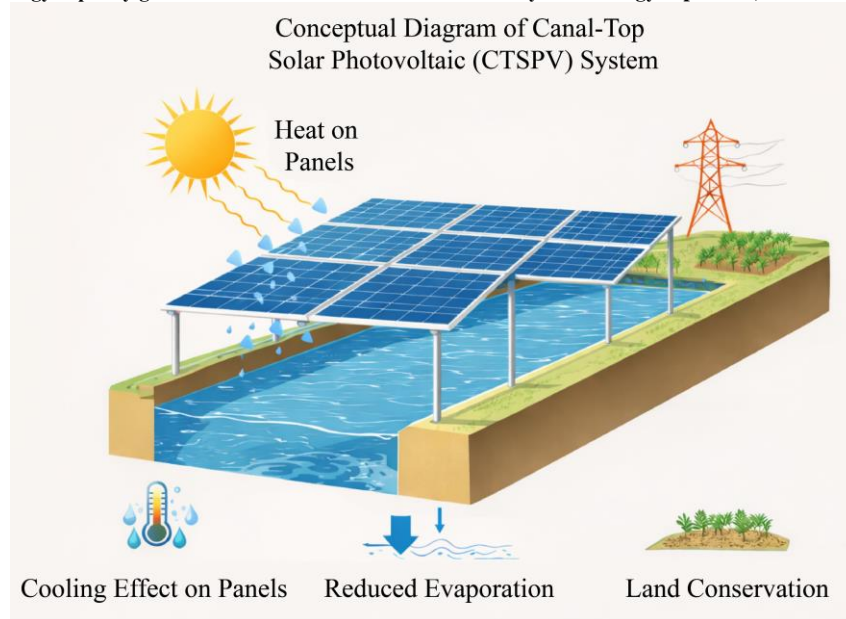


Fig. 4 Conceptual diagram of the CTSPV system.

5.2. Location of Solar Power Plant

The study incorporated distance to water resources as a significant criterion for both Economic Cost (EC) and Ecological Vulnerability (EV) models. The study recognizes that water is essential for solar power plants, particularly when cleaning and maintaining photovoltaic panels. Sites closer to water bodies are preferred for more efficiency, as they reduce infrastructure development costs for water access, and this proximity also facilitates easier maintenance and operation of the solar power plants [19]. In a CTSPV system, water is available just at the bottom, so the canal is the best site for a solar power plant, which can also be used for cooling purposes. Second point: generally, sites with annual radiation above 6,800 MJ/m² are classified as "high" suitability, while areas below 4,300 MJ/m² are considered unsuitable. Sunshine duration over 3100 hours annually is further required for a

favorable site [20]. Generally, the same site selection criteria are also applied to canals. The canal passes through high radiation and a hot environment [21]. Canal location may become one of the best sites for a solar power plant, and a canal-top solar power plant becomes a unique nexus.

5.3. Dust Penetration

The research emphasizes that deserted regions, despite having great solar potential and land availability, face dust deposition as the main challenge in successful PV system deployment. A single dust storm can cause up to a 20% power output reduction, highlighting the critical importance of understanding and mitigating dust penetration effects in solar installations [22]. Power loss due to partial shading and hot spots can be greater than 70% [23]. The loss of efficiency depends on the exact mass and size of the dust particle

deposition on the surface of the PV module. The deposition of the particles on the PV surface is forceful in the desert climate. Dust particles can reduce solar output by nearly 40%. Active cooling effectively removes dust penetration and enhances the performance of the solar panel [15]. In active cooling, fluid is required, and mostly water is used; this is available in the canal top SPV system, so that it can be a unique nexus.

5.4. Effect on the Ecosystem

Several studies indicate that FPV installation decreases water temperature. A decrease in water temperature affects fish spawning, leading to a reduction in fish populations. Lower dissolved oxygen reduces fish production, according to studies on integrated fish ponds. This oxygen depletion also poses direct threats to aquatic organisms. The complete eradication of algal blooms at 60-100% coverage could potentially harm the health of the ecosystem [28]. Algae serve as a primary food source for many aquatic animals. Reduced algal generation affects the entire food cycle. Large-scale FPV installations can cause risks to aquatic biodiversity. Large floating solar panels can alter aquatic ecosystems by blocking sunlight, affecting photosynthesis, water temperature, and dissolved oxygen levels. Careful environmental assessments and eco-friendly designs are necessary to mitigate ecosystem impacts [29].

5.5. Algae Growth

As discussed in the last point, algae growth is crucial for the ecosystem, but that will become a challenge when it comes to the canal. Algal proliferation in an 11 km irrigation canal increased Manning’s roughness coefficient by up to 73% (from 0.011 to 0.019), raising water levels by as much as 22 cm at full design flow and triggering overflow during peak irrigation. Cold-water species—*Ulothrix zonata*, *Hydrurus foetidus*, and diatoms—thrive between 5°C and 20°C, peaking at 13°C, which means that as the temperature of the

flowing water decreases, algae growth decreases [30]. These findings demonstrate that algal growth is a primary challenge to canal conveyance and flood risk management. FPV systems significantly impact aquatic ecosystems by reducing the amount of light that penetrates the water. Chlorophyll A concentrations were reduced by up to 30% [28]. Algal biomass in the Sheikh Zayed canal decreases by approximately 17% under full solar panel coverage, contributing to improved water quality parameters such as dissolved oxygen and nutrient concentrations. Solar panel coverage in canals reduces algal growth up to 19%, improves dissolved oxygen and nutrient profiles, controls evaporation, and generates renewable energy. Optimal partial shading (30–50%) balances water savings, water quality for irrigation, and power output. This passive approach mitigates algal blooms while enhancing canal sustainability and efficiency [27]. Shri S. S. Rathor, the managing director of the world’s first canal-top solar power plant, also mentioned that the CTSPV power plant can control algae growth, which is beneficial for the canal’s purpose [25].

5.6. Salt Deposition and Other Challenges

Generally, solar systems are installed in unused spaces such as road dividers, railway tracks, seawater surfaces, lake and river surfaces, and desert areas. Because of land unavailability. Out of the total free water surface available in the world, approximately 71% of the total surface area of the earth is approximately 361 million km² [25]. Seashore and seawater floating solar power plants are becoming more popular because of their huge area of availability. If salt deposition occurs on a seawater surface floating solar panel, its performance decreases. Performance decreased by approximately 6.7% in 10% salt concentration and 21.8% in 20% salt concentration compared to normal seawater conditions due to salt accumulation effects [31]. To overcome the adverse effect of salt deposition, canal top or canal floating installations are advisable.

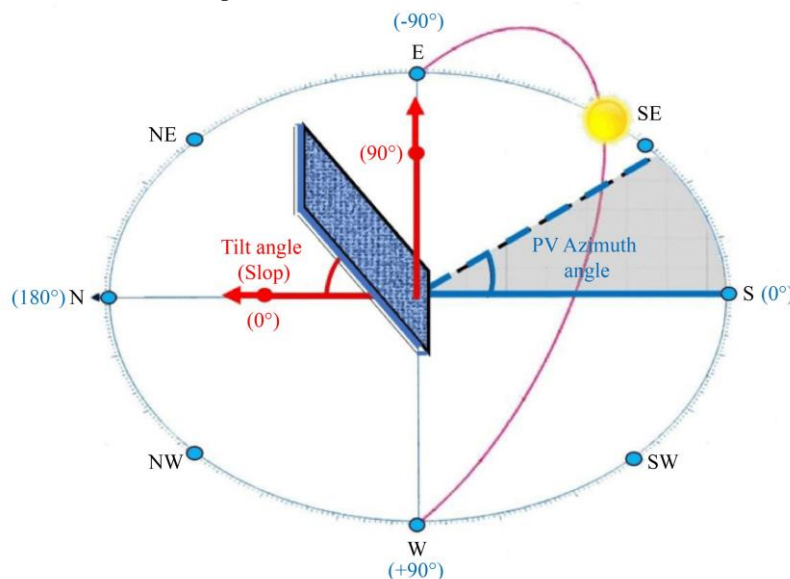


Fig. 5 Tilt angle and Azimuth angle of Solar Panel

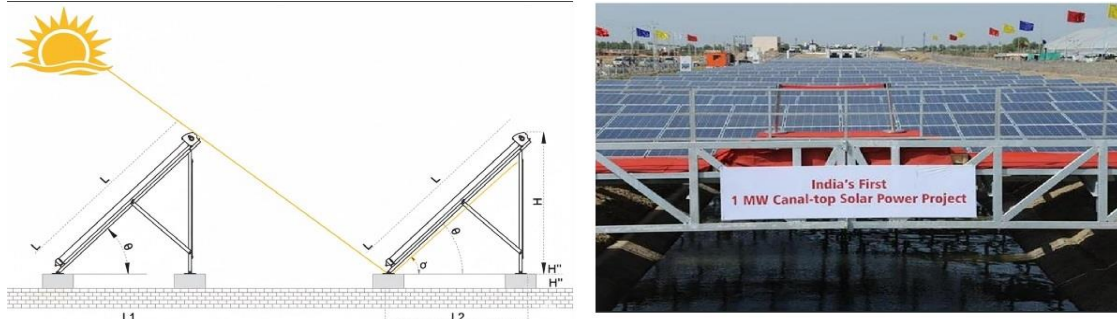


Fig. 6 Inter-array spacing arrangement



Fig. 7 Single slope due south direction arrangement

Table 1. Different types of panel arrangements on the canal or experimental setup.

Study Reference	Canal Direction	PV Panel Direction / Orientation and Configuration	Conclusion or Key Finding	Reference
Gujarat Pilot Project (1 MW)	North-South Direction	North-South orientation	Inter-array arrangement (suggested)	[18, 24]
Vadodara Project (10 MWp)	East-West Direction	Panels placed in a south-facing manner	Single slope, south-facing manner (suggested)	[18, 24, 25]
Tajo-Segura Transfer Scenario (Spain)	East-West Direction	Panels placed in a south-facing manner	Single slope, south-facing manner (suggested)	[24]
Canal Top with Reflectors (Conceptual)	East-West Direction	Panels placed in a south-facing manner	Single slope, south-facing manner (suggested)	[26]
Canal Top with Reflectors (Conceptual)	North-South Direction	North-South orientation	Inter-array arrangement (suggested)	[26]
Experimental PV Technology Comparison (Experimental)	Water tank	south-facing direction	Inter-array arrangement (suggested)	[27]
Sheikh Zayed Canal (Egypt)	North-South-East Direction	South-facing (suggested)	Both patterns suggested	[27]

Saltwater is highly corrosive, so corrosion is a major challenge for the durability of solar panels and floating structure components when installed offshore. Advanced corrosion-resistant materials become more essential to ensure long life. Furthermore, offshore and coastal floating solar installations must withstand strong waves, tides, and dynamic water forces. So robust systems, wave-absorbing designs, and buoyant platforms are required to maintain stability and performance [29].

5.7. Evaporation Loss

Canals are engineered channels designed to convey water from sources (rivers, reservoirs, groundwater recharge basins) to regions where natural availability is insufficient. In water-scarcity zones, canals serve several critical functions, and one of the main functions is irrigation. In arid and semi-arid climates, open-channel canals can lose 30–50% of their carried water to Evaporation annually [32]. By combining structural improvements, operational changes, and innovative coverings, canals in water-scarce regions can be made far

more efficient—ensuring that a greater proportion of precious water actually reaches end users rather than dissipating into the atmosphere. Floating solar panels, also known as Floating Photovoltaic (FPV) systems, significantly reduce water evaporation through shading effects. Research shows FPV systems can reduce Evaporation by 60 to 90%. This water-saving potential is substantial; if 27.5% of China's inland waters were covered with FPV, the water savings would be equivalent to the entire South-to-North Water Transfer Project volume (44.8 billion m³) by 2050 [28]. By installing Photovoltaic (PV) panels atop canals, direct solar radiation on water is blocked, which cuts Evaporation and cools the panels. PV panels are devices that convert sunlight into electricity. This approach conserves roughly 9 million L of water per MW per year and achieved a saving of about 7 million L annually in the Thummalapalem demonstration [18]. In the Sheikh

Zayed canal case study, annual water loss of 8.64 million m³ without cover can be cut by nearly one-third (to 5.85 million m³) at 33% coverage and by almost half (to 4.39 million m³) at 50% coverage, reaching near-zero loss at full coverage [27]. The installation of the 10 MWp canal-top photovoltaic (PV) plant at Vadodara, Gujarat, reduces annual water evaporation by approximately 95.5 million L, calculated via a USGS empirical formula, with year-to-year variation of just under 1% [33]. The Canal-Top Solar Power initiative significantly reduces water losses due to Evaporation; for example, a 1 MW project can conserve 9 million litres of water annually, and a 10 MW project can conserve 90 million litres of water annually [34]. From the detailed literature review, as shown in Table 2, there is a huge saving in Evaporation, and that saving in water again strengthens the purpose of the canal.

Table 2. Saving in Evaporation is noted in the literature review.

Author	Location	Savings in Evaporation in percentage or quantity	Reference
Gallego-Elvira et al.	Southeastern Spain	up to 85%	[35]
Aminzadeh, Lehmann	Majadas, Spain	approximately 88.6%	[36]
Taboada et al.	Northern Chile	up to 90%	[37]
Bontempo Scavo et al.	Biviere Lake, Lentini, Catania, Italy	up to 49%	[38]
Abdelal	Amman, Jordan	60%	[39]
Santos et al.	Passaúna Reservoir, Paraná State, South Brazil	60.20%	[40]
Alam & AlShaikh	Saudi Arabia	58%	[41]
Al-Hassoun et al.	Experimental setup, location unspecified	63%	[42]
Mittal et al.	Jodhpur, India	191.174 million litres per year for 1 MW FPV	[43]
Manish Kumar et al.	Sama, Vadodara, India	95.54 million litres per year for a 10 MW canal top	[33]
El Baradei et al.	Toshka, Upper Egypt (Sheikh Zayed Canal)	approximately 4.25 million m ³	[44]
Quaranta et al.	Europe (General assessment/modelling study)	reduced by 70%	[45]
Martin's	Sonoma County, US	Estimated savings up to 23,250 m ³	[46]

Table 3. Efficiency gain noted in the literature review.

Author	Condition	Efficiency Difference	Reference
Nisar and others Charles et al. (as cited by Nisar et al.)	FPV system comparison to on-ground PV system at 0° tilt angle	20% to 28%	[47]
Charles and others	Thermo-electrical performance assessment	1% to 2%	[48]
Liu and others	Power generation efficiency and prospects	1.58% to 2.00%	[49]
do Sacramento and others	Scenarios for the use of FPV plants in Brazilian reservoirs	9.52% to 14.5%	[50]
Yadav and others	Energy assessment of a floating PV system	0.79%	[51]
Majid and others	Study on the performance of an 80 W floating PV panel	15.5%	[52]

Hammoumi and others	Design and construction of a test bench to investigate the potential of floating PV systems	2.3%	[53]
Osama and others	Partially Submerged PV System (PSPV) vs. OPV	18%	[54]
Tina and others	Comparison of FPV vs. OPV	3.4% to 7.3%	[55]
Liu and others	FPV system vs. ground system on an artificial pond	0.79%	[56]
Srinivasa Murthy and others	10% submerging of solar panels in a water body	18%	[57]
Sahu and others	Submerged panels (in summers) compared to a normal panel exposed to the air	20%	[58]
Azim and others	Comparison of a floating panel with a ground-mounted one	3.61%	[59]
Trapani and others	Review of floating photovoltaic installations	20% to 25%	[60]

5.8. Performance and Output

FPV systems demonstrate enhanced performance compared to land-based installations. 10% average efficiency increase due to water-cooling effects. Efficiency improvements range from 1.2% to 55%, depending on location and conditions [28]. Many studies have been carried out on water bodies to measure performance as compared to land-mounted solar panels, and most of the studies conclude that the performance of water-top solar panels is improved due to the cooling effect. The study is summarised in Table 3.

5.9. Life of Panel and Degradation

Land-based solar panels have a higher temperature than CTSPV, as was mentioned in the previous point. As surface temperature increased, the life of the panel decreased [61]. The standard operating condition for the panel is a 25°C module temperature, and the nominal operating cell temperature is 45°C; above 45°C, critical degradation is shown in panel life [15]. The 10 MW canal-top, grid-connected photovoltaic plant studied concludes that there is a significant performance degradation of $1.93 \pm 0.28\%$ per year in its early operating life, which is higher than typical ground-mounted crystalline silicon systems (0.8%/year) [33, 62]. The numerical data show that coastal PV installations face a unique degradation challenge, which can cause a loss of energy of up to 26% as compared to inland installations. The light-induced degradation rate of 2.7% per year, along with temperature-related losses of 9.7%, shows that there are faster degradation processes in coastal areas. These processes need targeted solutions to ensure the best long-term performance [63]. Water-based solar PV systems consistently show higher degradation rates than land-based systems. The research reveals that while floating solar PV (FSPV) and CTSPV initially offer a 10-15% energy gain, they later face a 15-30% drop in efficiency due to the effects of humidity [64].

5.10. Land Conservation

One of the main concerns in solar PV systems is that they require huge land areas, and the same is compensated for in

the CTSPV system. In the CTSPV system, unused space is utilised for power production and other benefits, as previously discussed, and this is successfully achieved. Implementing SPV arrays atop irrigation canals can eliminate the need for nearly 15 acres of land for a 641.6 kW installation, translating to a land saving of approximately 100 ft² per kW compared to ground-mounted systems [18]. Installing Photovoltaic (PV) arrays offshore on water bodies entirely avoids the need for scarce agricultural land on small islands like Malta, preserving state-owned farmland that accounts for two-thirds of total agricultural land and contributes approximately 2% of national GDP when in production. Offshore floating PV of the same capacity would thus save 15–20 hectares of agricultural land per 10 MW installed, multiplied proportionally for larger projects [65]. The total area of the Bhadla Solar Power Park spans such a huge 5,783 hectares [66]. The installation of the 10 MWp PV plant on the 3.6 km-long Vadodara branch irrigation canal resulted in saving 25 acres of prime land. This represents a significant conservation of valuable land resources that would otherwise have been required for a conventional ground-mounted solar installation [33]. A 1-MW pilot project saves approximately 6 acres of land while generating 1.6 million kWh annually and saving 9 million litres of canal water per year. Further, a 10 MW installation on the Vadodara Branch Canal conserves about 25 acres of land, producing 16.2 million kWh each year [34, 62, 67]. A solar power plant with a capacity of more than 20 MW requires around 7.9 acres per MW of total land area [68].

Installing photovoltaic panels on the open sections of the Tajo–Segura water canal avoids the need to clear or acquire additional ground for a conventional solar farm, preserving 195.41 hectares of land that would otherwise be required for a free-standing installation [24]. CTSPV uses the existing canal infrastructure, effectively saving 100% of the land that would otherwise be needed for the same capacity on the ground [46]. By deploying Floating Photovoltaic (FPV) panels on 10% of Spain's continental freshwater surface

area, 419.4 km² of land could be conserved compared to equivalent ground-mounted PV installations [69]. As of 2019, approximately 3300 km² of land was used for solar power production globally, while 12.44 million km² of land was used for agricultural purposes [13]. By moving PV installations offshore (floating PV arrays), all of the land area that would otherwise be occupied by ground-mounted panels is preserved for agriculture, eliminating this trade-off and safeguarding food-production capacity [18, 25, 3362, 70, 67, 71, 72, 73, 74]. India has approximately 46.7 million hectares of wasteland available for utility-scale solar power plants. Developing on wasteland does not create environmental pressure on agricultural systems, as it allows for the utilisation of land that is otherwise unproductive and preserves fertile agricultural land for food production. Further innovative concepts like the CTSPV system and the floating SPV system were introduced to save land, and in that, by the cooling effect, performance also improved, so the space required is also decreased [75].

CTSPV systems are often installed along major irrigation canals that run parallel to or near existing power transmission lines. This proximity reduces the cost of grid connectivity compared to remote ground-mounted solar farms. The canal

infrastructure also provides access routes for maintenance vehicles, reducing last-mile connectivity costs. Grid integration of CTSPV systems in India has been studied in the context of the Gujarat canal-top pilot project, where the 1 MWp installation was successfully connected to the state grid [33].

6. Comparative Analysis of Land-Based SPV and CTSPV Systems

Based on the literature review and parameter analysis discussed in the previous sections, a comparative evaluation between conventional Land-Based Solar Photovoltaic (LSPV) systems and CTSPV systems is presented in Table 4. This comparison highlights the technical, environmental, and economic differences between the two technologies.

The comparative analysis indicates that CTSPV systems provide several advantages, such as land conservation, improved cooling, evaporation reduction, and better environmental integration, although the structural cost of installation may be slightly higher than conventional land-based systems.

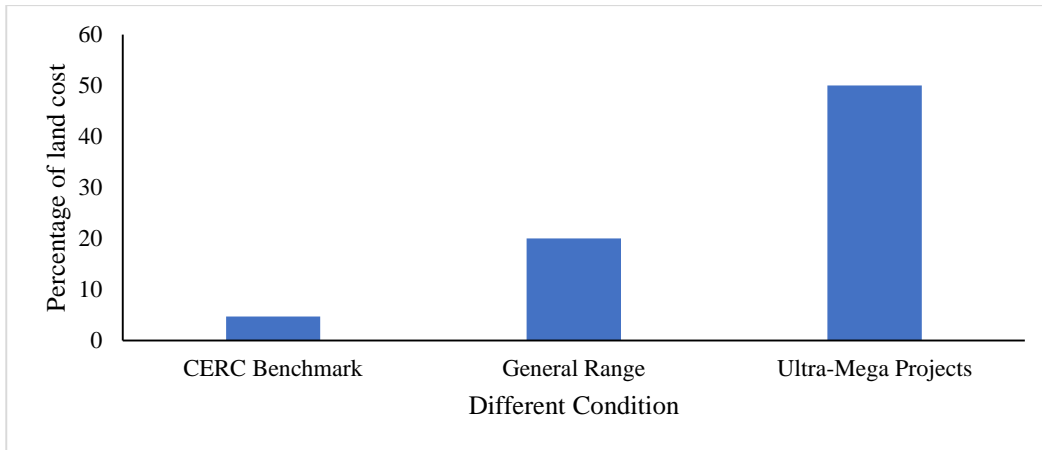


Fig. 8 Land cost in solar power plant

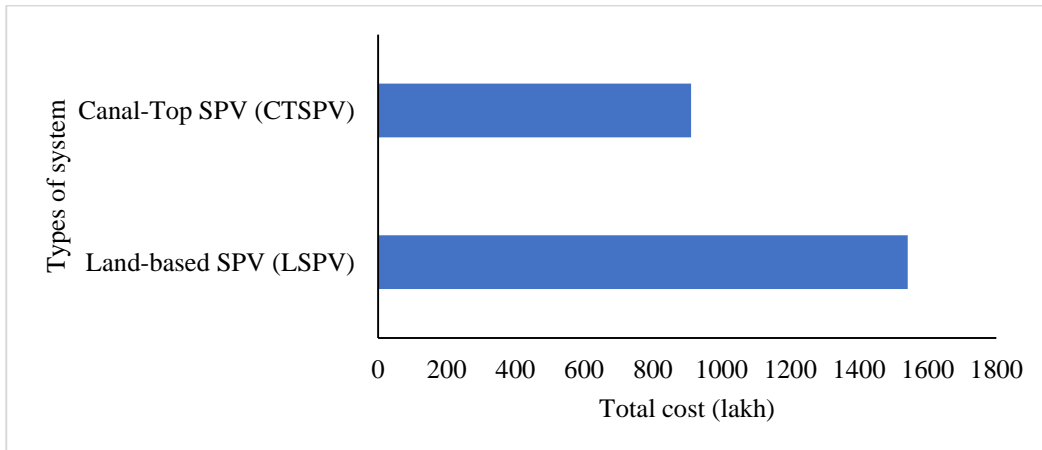


Fig. 9 CTSPV is 40.99% cheaper when land cost is included.

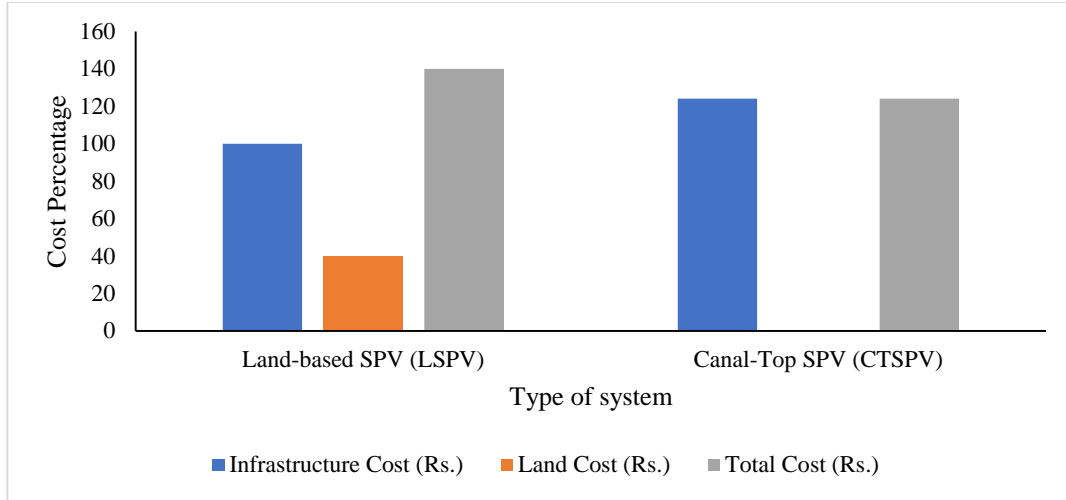


Fig. 10 Without land cost, CTSPV is 24% costlier. Land elimination is the main saving factor.

Table 4. Comparative analysis of Land-Based Solar Photovoltaic (LSPV) and Canal-Top Solar Photovoltaic (CTSPV) systems

Parameter	Land-Based Solar PV (LSPV)	Canal-Top Solar PV (CTSPV)
Land Requirement	Requires a large land area (approximately 4–5 acres per MW)	No additional land required; installed over existing canal infrastructure
Panel Cooling	Limited natural cooling; higher module temperature	Natural cooling due to the proximity of the water surface
Efficiency	Standard efficiency depending on ambient conditions	An efficiency increase of about 5–10% due to the cooling effect
Water Evaporation	No effect on water bodies	Reduces canal water evaporation by approximately 60–90%
Dust Accumulation	Higher dust deposition, especially in desert regions	Reduced dust accumulation due to higher humidity and easy water cleaning
Land Acquisition Issues	Major challenge due to land availability and cost	Eliminates land acquisition and development issues
Environmental Impact	May affect agricultural land and land use patterns	Improves water conservation and reduces algal growth
Infrastructure Cost	Lower structural cost	Higher structural and installation costs
Overall Economic Feasibility	Lower installation cost but high land cost	Slightly higher installation cost, but economical when land cost is included

7. Favorable Parameters as Compared to the Existing (Land-Based) SPV System

7.1. Panel Surface Temperature

As the temperature rises, the performance of Photovoltaic (PV) modules deteriorates. Specifically, the open-circuit voltage (Voc) decreases notably with increasing temperature, while the short-circuit current (Isc) sees only a slight increase. This results in a net reduction in the maximum power output (Pmax) of the modules. For crystalline silicon (c-Si) panels, efficiency declines by approximately 0.4–0.5% for each degree Celsius above 25°C [15]. PV panels convert only 15–20% of solar energy to electricity; the rest becomes heat, raising surface temperature up to 80–90°C under strong

sunlight (1000–1050 W/m²). Electrical efficiency drops by about 0.4–0.65% for every 1°C temperature rise due to reduced open-circuit voltage and increased charge carrier recombination [76]. Effective thermal management of PV panels can enhance electrical efficiency by 5–30%, increase power output, and extend module life [77].

7.2. Cooling Technique

Cooling of solar photovoltaic panels is essential because panel efficiency decreases by approximately 0.5% per 10°C rise in temperature. Both passive and active cooling methods significantly reduce operating temperature and improve electrical efficiency, but their effectiveness varies. In passive cooling, the temperature drop is 10–25°C, while in active

cooling methods such as forced air, water, and thermoelectric cooling, greater temperature drops are achieved (23–35°C, up to 49°C with water), but they require external power [78].

7.3. Economic Benefits of the CTSPV System

According to the last point, the CTSPV system conserves land and allows it to be utilized for other purposes. However, if land costs are taken into account when calculating the cost of a solar power plant, the CTSPV system becomes more cost-effective than a land-based solar power plant. The data related to land cost for solar power projects by the Central Electricity Regulatory Commission (CERC) of India in Petition No. SM/353/2013 is 18.00 lakh per MW [79]. For the financial year 2016–17, the Central Electricity Regulatory Commission (CERC) considered the land cost at Rs. 25 lakh per MW [80]. The land for the Pavagada Solar Park is being leased from farmers, rather than purchased. The annual lease rent for the land is Rs 21,000 per acre (US\$300). The project is spread across 13,000 acres in Karnataka's Tumkur district. The total compensation paid for all the land required for the park amounts to ₹23–25 crore per year.

The annual payment will increase by 5% every two years. The lease is typically valid for 25–35 years. The initial rate was ₹21,000 per acre for the first five years, with a 5% increase every two years [81, 82]. The same type of model is used with some modifications in the Pavagada Solar Power Plant, Karnataka, where the initial rate is adjusted based on the same 5% increase every two years, leading to a significant increase in revenue over the lease period. The total expected revenue gained by a landowner for every 5 acres of land at the end of the 28-year lease period is projected to be around Rs. 64 crores, and the total cost of 12616 acres is approximately Rs. 1,600 crores [83]. The values for land cost also vary by a big margin from state to state, depending on the affinity to the nearby township [84, 85].

For the financial year 2016–17, the Central Electricity Regulatory Commission (CERC) considered the land cost at Rs. 25 lakh per MW, which was 4.7 per cent of the total cost [80, 86]. The cost of land generally ranges from 5% to 20% of the total solar project cost [87]. The cost of the land and its development combined will be approximately 40–50% of the total project cost in ultra-mega solar power projects [88, 89]. Figure 8 shows the percentage of land cost in a solar power plant. The type of land and the land-acquiring method are variable (indirect) factors that influence the unit cost of power generation, as they can significantly affect the overall financial feasibility and operational efficiency of solar power projects. In the same way, all over the world, like Malaysia [90], Taiwan [91], Bangladesh [92], Israel [93], Province of Tarlac [94], Sudan [95], etc., land cost in percentage and absolute cost data is available. Generally, the LCOE parameter is used to find the land cost, and some other method is also introduced for a land cost Module-to-Land cost ratio (ML) [96].

If land cost is not considered, then the CTSPV system becomes about 24% more costly than the LSPV system [97, 98, 99]. In most countries, Austria, Germany, and Great Britain, the CTSPV system installation cost is higher because of higher infrastructure, and if land cost is considered, then the CTSPV system becomes more economical [24, 58]. In India, if the land cost is considered, then the total cost of the land-based solar power plant, which is designed to generate 641.6 kW, is Rs. 15,41,77,000 with the land cost of village Thummalapalem, while the same power plant installed on the canal top costs Rs. 9,11,77,000.

Here, the present review shows that the cost of a CTSPV is 40.99% cheaper than the land-based solar system [18]. As shown in Figure 9, CTSPV is cheaper than an LSPV. Finally, this review can conclude that if land cost is considered, then the CTSPV system becomes cheaper; otherwise, it will become costlier, as shown in Figure 10.

8. Future Scope

The investigation of CTSPV systems highlights several future research directions, including increasing long-term durability, improving system performance, and changing the economic modelling of solar photovoltaic systems.

8.1. Degradation and Durability

Solar PV systems based on water, such as CTSPV, tend to degrade more rapidly than ground-based systems. One study noted that there was a 1.93% decrease in annual performance for a CTSPV plant, while for a ground-mounted plant, it is 0.8%. Future research needs to minimise humidity-caused efficiency loss and use corrosion-proof materials to enhance durability, particularly for floating components.

8.2. Optimal Design for Fixed Canal Directions

In CTSPV systems, the direction of the canal restricts the placement of solar panels. Future research needs to investigate ways to optimally adjust the tilt angle, which depends on location, latitude, solar declination angle, and sunset hour angle, even when a fixed installation is required year-round. More research is required on optimal panel layout and inter-array spacing for north-south canals. Conceptual systems, like Canal Top with Reflectors, noted for both east-west and north-south canal orientations, need thorough practical and simulation-based investigations to prove efficiency improvement.

8.3. Cooling and Cleaning Systems for the CTSPV System

As water is easily accessible under the CTSPV system, future development potential involves creating advanced active cooling systems based on canal water to enhance solar panel efficacy and efficiency even more. Additionally, actively preventing dust penetration with this accessible water is a very significant area for evolution, as dust can reduce solar power by close to 40% in desert environments.

8.4. Improvement in Economic Modelling

Economic viability depends heavily on land cost and its development, with the latter contributing anything from 5% to 20% (and even 40-50% for ultra-mega schemes) to the entire solar project cost. Though land destruction renders CTSPV extremely cost-effective in land-constrained areas such as India, the scope in the future includes the enhancement of the calculation of the Levelised Cost of Energy (LCOE) and other cost factors, including the Module-to-Land cost ratio (ML), to offer a benchmark, location-specific economic comparison with land-based systems.

9. Conclusion

The review summarises that CTSPV systems provide a robust, green, and efficient power generation alternative, overcoming significant challenges with traditional Land-Based SPV (LSPV) systems. The most important advantage of CTSPV is the preservation of land value by making use of existing canal infrastructure, thus eliminating land acquisition, availability, and administrative clearance challenges.

Land conservation is considerable; for example, a 10 MWp project in Vadodara conserved 25 acres of valuable land. When the high cost of land is added to overall project expenses, CTSPV systems are very cost-effective, usually being cheaper than LSPV systems (one instance revealed a CTSPV system to be 40.99% less expensive). Without costs for land, however, CTSPV is still more infrastructure-oriented and can be as much as 24% more expensive. Additionally, CTSPV systems create a distinct water-energy nexus by increasing operating efficiency and fostering water conservation:

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9.1. Increased Efficiency

The cooling effect achieved from the underlying water body decreases the top surface temperature of the solar panels, which otherwise leads to a loss of efficiency in LSPV. Research attests to an average efficiency gain of 10%, with improvements measured between 1.2% and 55%.

9.2. Evaporation Reduction

Under desert and semi-desert environments, where canals lose 30–50% of water each year, CTSPV systems effectively lower evaporation by shielding the water surface, bringing down evaporation reductions as low as 60% to as high as 90%. For instance, a 1 MW pilot project can save around 9 million litres of water each year.

9.3. Water Quality and Maintenance

Panel coverage regulates algal growth, which otherwise complicates canal conveyance and flood risk management. Access to water also offers a resource for active cooling and washing, preventing power loss due to dust penetration in high-radiation areas.

But careful site-specific planning is necessary for the deployment of CTSPV systems, with special attention to the uncontrollable canal orientation that determines optimal panel tilt and spacing. Moreover, the increased degradation rates in water-based systems make ongoing research into materials and design a necessity for long-term durability and performance, particularly in order to ensure that these systems can withstand environmental factors and maintain efficiency over time. In general, CTSPV systems represent a significant technological advancement for nations like India, which aim to achieve high growth rates and ambitious net-zero carbon emissions by 2070.

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