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Underwater solar panels in Aotearoa New Zealand: An economic analysis

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Abstract
The global shift toward renewable energy sources has intensified research into innovative solar energy solutions. One promising avenue is submerged photovoltaic solar panels (SP2), which leverage water cooling to enhance efficiency while addressing land use constraints. This study conducted an economic analysis of SP2 technology in the Aotearoa New Zealand context, comparing its viability to conventional land-based photovoltaic (LPV) and floating photovoltaic (FPV) systems. Using a cost-benefit analysis (CBA) framework, capital expenditures (CAPEX), operational costs, efficiency gains, and potential financial returns of SP2 farms were assessed. The findings indicate that while SP2 panels offer improved cooling and potential efficiency gains, these advantages are largely offset by higher installation and maintenance costs, biofouling risks, and structural challenges. Sensitivity analyses suggest that material advancements—particularly in GaInP and CdTe solar cells—could improve SP2 feasibility in the long term if manufacturing costs decrease. Additionally, the study highlights niche applications where SP2 could complement agricultural activities by preserving farmable land while providing renewable energy. Despite current economic limitations, SP2 technology remains a promising research direction, with potential improvements in cost efficiency, durability, and deployment strategies. Future work should focus on large-scale pilot projects, material innovation, and environmental impact assessments to refine the feasibility of underwater solar farms as a viable component of the renewable energy landscape.

Keywords: Submerged photovoltaics; Solar energy; Economic performance; Feasibility.

1. Introduction
The world is facing a climate crisis that needs to be addressed, among others, in the way we produce energy. We need to reduce our fossil fuel use while the global energy demand keeps increasing year-after-year, as shown in Figure 1 (Maduko, 2013). Electricity is at the forefront of the energy crisis, making the pursuit and development of renewable energy both urgent and essential for achieving a more sustainable power grid.

Over the last 20 years, two technologies have emerged and are now the most promising candidates to reduce stress on the grid and reliance on fossil fuel. Wind and solar plants keep getting less expensive and more efficient, and growing investments in those sectors suggest that the next few years will revolve around them. For example, Figure 2 shows that in the Aotearoa New Zealand context most new generation projects are targeting solar and wind (Concept Consulting, 2023). However, both these technologies suffer from efficiency limitations. The average efficiency range for offshore wind farms is between 35 to 50% (Bilgili, 2020) and for solar plants from 21% to 27% (NREL, 2024).

Likewise, land use, space limitation and competition with other sectors, especially agriculture, make the deployment of large-scale projects either a difficult process, filled with compromises and higher cost to adapt to the land, or an impossible one in sites where the topology is not suitable for implementation or where space constraints are too important. These limitations are a challenge for Aotearoa New Zealand. Out of the 156,55 Petajoule of electricity generated in 2023, 11,54 came from wind farms, and only 1,32 from solar plants (MBIE, 2024).

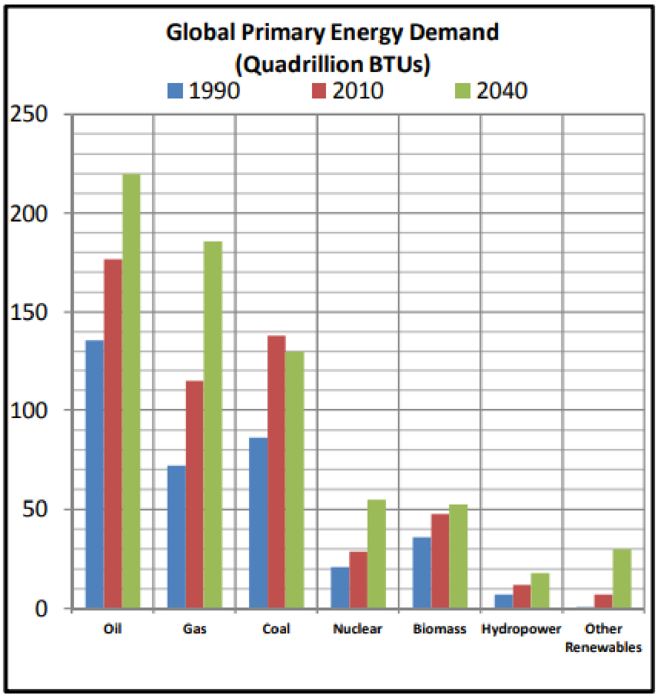


Figure 1. Projected global primary energy demand
(Source: Maduko 2013)

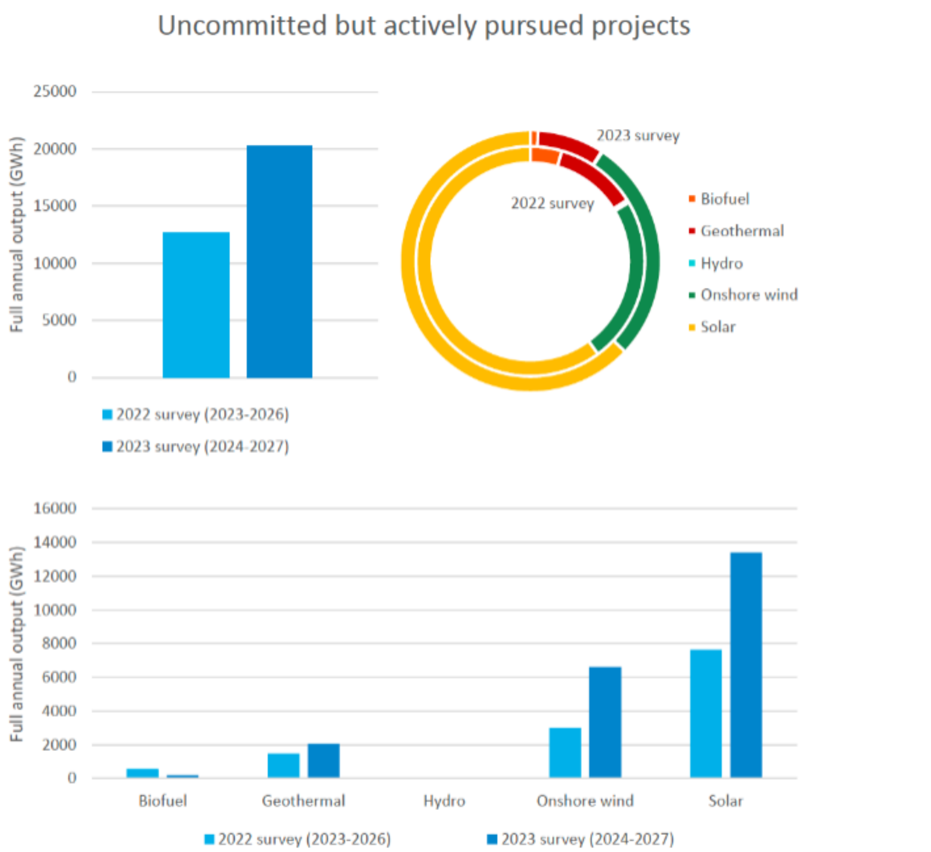


Figure 2: Uncommitted but actively pursued projects in Aotearoa New Zealand
(Source: Concept Consulting, 2023)

To overcome these challenges, wind farms have moved from the land to the sea. Offshore wind farms get a better wind exposure and are not subject to land occupation issues. Following that path, solar plants could also relocate to the ocean or other water bodies. Floating PV (FPV) plants is a solution both feasible and viable, and a research topic that is rapidly gaining traction due to its potential (Ramanan, 2024). Its extension, submerged photovoltaic solar panels (SP2), shows promising results that could outmatch its land counterpart.

1.1. Objective of the paper

The objective of this study is to provide a comprehensive outlook on SP2 farms, a potentially untapped market. First it determines the different costs associated with SP2 systems. This includes materials, waterproofing of the PV cells, coating to protect from corrosion, along with infrastructure and maintenance cost that are different from regular PV plants. Secondly, the aim is to contrast all those additional costs with the benefits in efficiency gain from using underwater PV. Using the collected data, a final cost-benefit analysis (CBA) was undertaken to present the competitive advantage and/or disadvantage of the SP2 system in the renewable energy market.

1.2. Limitations and assumptions of the study

This study is limited by the total knowledge surrounding SP2 due to its novel nature. This could be challenging for the analysis because, although laboratory tests have been conducted on SP2, there is no data on the life cycle of underwater solar panels, their efficiency under real-life conditions such as stormy weather and murky water, or the degradation rate of such technology. To facilitate the study, some assumptions had to be taken regarding those missing data and sensitivity analyses were undertaken.

1.3. Research approach and strategy

This study followed a deductive research approach, based on a positivist research philosophy. It started by analysing existing literature to establish a fundamental baseline for the SP2 technology. Missing data were filled in with reasonable assumptions from relevant secondary sources. Subsequently, an economic analysis was performed to assess the quantitative performance of a SP2 system compared to a land based photovoltaic (LPV) solar farm, allowing for an evidence based preliminary conclusion. Finally, the validity of the conclusions is discussed through a sensitivity analysis that was undertaken. This overall research strategy is summarized in Figure 3.

2. Literature review

This section focuses on the potential of underwater PV systems as a promising alternative to traditional solar energy solutions. Through a comprehensive literature review, we explore recent technological advancements in submerged PV systems, particularly in terms of efficiency gains, cooling mechanisms, and material adaptation for underwater environments. The review assesses various solar cell technologies, including monocrystalline, polycrystalline silicon, indium gallium phosphide (GaInP), cadmium telluride (CdTe), organic solar cells (OSC), and perovskite solar cells (PSC), analysing their performance in aquatic settings and their potential to overcome land-based limitations. Challenges such as light attenuation, corrosion, hydrostatic pressure, and biofouling are discussed, alongside economic considerations crucial for the future viability of underwater solar farms. Despite the technical hurdles, underwater PV systems offer significant potential, with promising efficiency improvements in shallow waters and material advancements showing increased resilience. By identifying knowledge gaps and synthesizing current research, this paper aims to provide a foundation for future work in underwater photovoltaics, contributing to the diversification and expansion of renewable energy technologies.

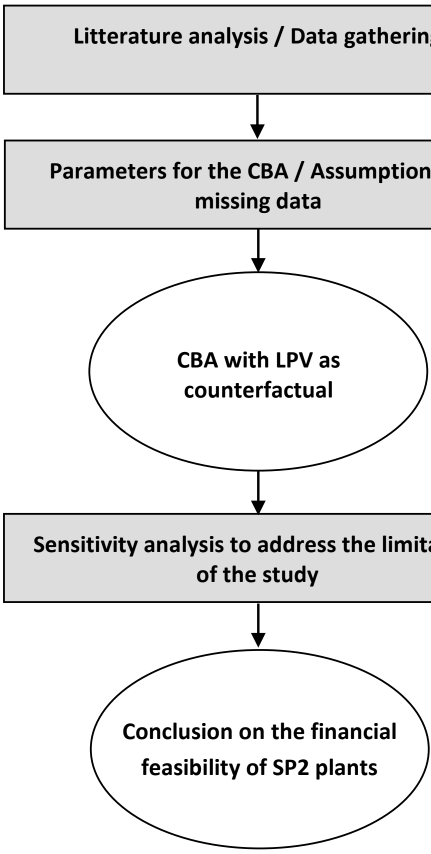


Figure 3. Strategy of the research study

2.1. Initial research

Rapid growth in global energy demand, coupled with growing environmental concerns, has led to a significant expansion of the renewable energy sector in recent decades. Among these clean energy sources, solar PV has emerged as a key technology, offering a promising solution for sustainable power generation (Siecker et al., 2017). However, faced with persistent challenges such as limited available land space and the need to improve the efficiency of PV systems, researchers and engineers are continually exploring innovative approaches to optimize this technology. In this context of innovation, the concept of underwater photovoltaic panels has emerged as a particularly interesting avenue of research. This innovative approach involves partially or fully immersing PV modules in water, thus exploiting the vast expanses of water available while potentially benefiting from the unique properties of the underwater environment (Rosa-Clot et al., 2010). Submarine PV installations offer several potential advantages, including natural cell cooling, reduced water evaporation in tanks, and efficient use of space in areas where land surfaces are limited (Kumar et al., 2020).

Initial research in this field has revealed promising results. Rosa-Clot et al. (2009) proved that monocrystalline solar cells show an increase in efficiency of about 10% in shallow water. These figures were significantly higher than the typical performance of land-based PV installations, underlining the considerable potential of this technology. Nevertheless, harnessing solar energy in the aquatic environment also presents its own challenges. Factors such as light attenuation in water, corrosion, hydrostatic pressure, and temperature variations must be carefully considered in the design and deployment of these systems (Stachiw, 1980). Furthermore, optimizing solar cell technologies for the underwater environment requires a thorough understanding of the complex interactions between light, water, and photovoltaic materials (Jenkins et al., 2013).

2.2. Efficiency gains

The main advantage of underwater solar PV is the cooling of the cells, reducing thermal drift, and increasing efficiency. This section examines the different solar cell technologies studied for underwater applications, their specific characteristics, and the technical challenges associated with their use in this particular environment. The solar cell technologies evaluated for their potential underwater use are mono and polycrystalline silicon cells, CdTe, GaInP, PSC and OSC.

Monocrystalline and polycrystalline silicon solar cells, widely used in terrestrial applications, showed promising results for shallow water environments. The investigations of both Mehrotra (2014) and Abdulgafar (2014) found an increase in efficiency of up to 18% for depths between 1 and 6cm. However, SP2 has shown a significant reduction in performance in deep water conditions. Rosa-clot et al. (2009) demonstrated a 35% reduction in efficiency for a 40cm depth in deionized water, while the study of Enaganti et al. (2020) revealed a power reduction of 65.85% for monocrystalline cells and 62.55% for polycrystalline cells at a depth of 20 cm in ocean water. Despite this drop, Stachiw (1980) reported that high-efficiency silicon cells can still generate 5-10% of their atmospheric power for up to 30m depending on the time and weather condition. Although at such depth only small electronic components could be powered by solar cells, this demonstrates the potential for specific underwater applications of SP2. Sill, previous numbers (see Figure 4) indicate that this material is not best suited for underwater use of solar panels.
In comparison, GaInP cells prove particularly suitable for underwater applications. Jenkins et al. (2013) demonstrated that these wide-bandgap cells outperform silicon cells by a factor of 2 to 3, at depths between 2.7 and 9.1m. Later, Röhr et al. (2020) demonstrated that underwater solar cells can achieve theoretical efficiencies ranging from 55% in shallow water to over 65% in deep water, with power densities exceeding 5 mW/cm^2 making them one of the most promising technologies for this application. However, high production cost is still a hindrance in the democratisation of this technology (Walters et al., 2015).

CdTe cells also showed superior performance in deep underwater environments. Röhr et al. (2020) found that CdTe cells outperform SP2 at depths greater than 2 meters, due to their wider bandgap, which better matches the light spectrum filtered by water. The technology already being industry-ready is a big incentive to use it, with companies such as First solar already having a nameplate capacity of 16.5GW (First solar, 2023).

Organic solar cells (OSC) appear to be a good candidate as well for underwater PV use. Walters et al. (2015) designed multi-junction OSCs specifically optimized for the underwater environment, and Wang et al (2024) managed to obtain a power conversion efficiency of 25.6% in shallow waters. OSCs have the advantage of being flexible and potentially less expensive to produce than GaInP cells, which could be beneficial. However, they have yet to be produced on a large scale, which is reflected on their current cost.

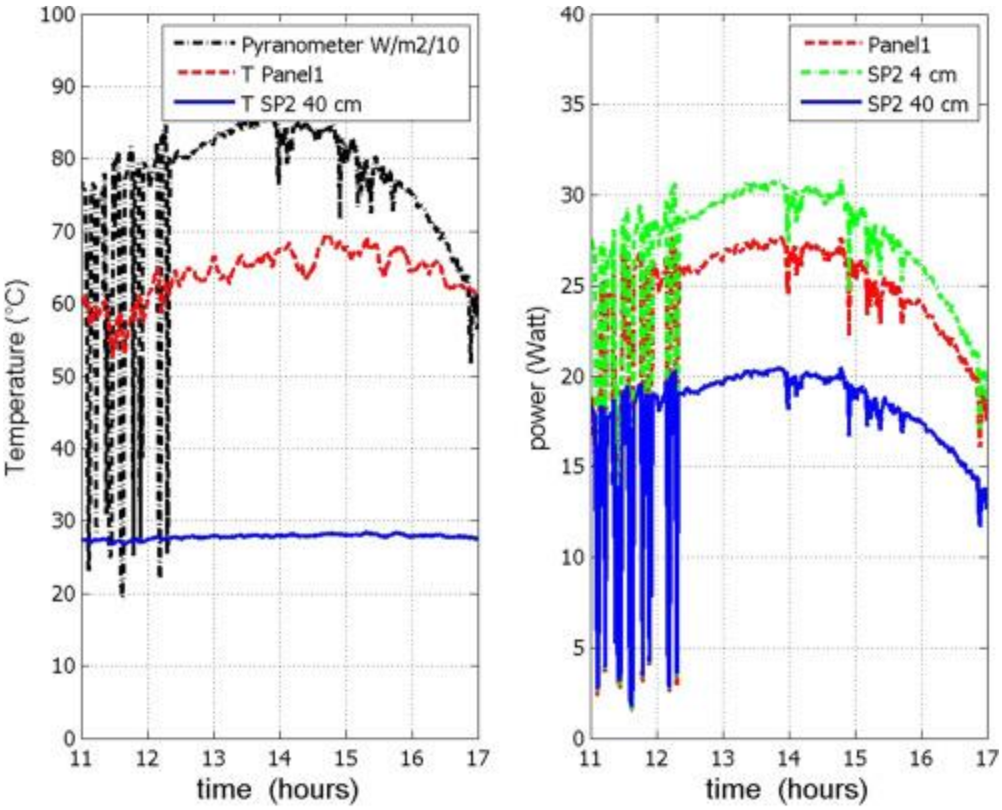


Figure 4. Measurement of PV conversion at different depth
(Source: Tina, 2017)

Finally, PSCs showed potential for underwater PV (Rörh, 2022). The material comes with a variety of bandgap values that could perform well in an underwater setting. Liu et al. (2022) achieved a power conversion efficiency (PCE) of 41.9% with them, even in deep water. However, toxicity and a low resistance to corrosion are still concerning issues revolving around this technology, especially when water immersion exacerbates those flaws. Furthermore, it hasn't been used outside of laboratory experiments yet.

2.3. Challenges and limitations

No matter the materials used in the manufacture of underwater solar cells, it must be stable in an aqueous environment, even during poor weather, resistant to corrosion, and capable of maintaining their performance over extended periods of immersion (Rosa-Clot et al., 2010). This stability is crucial to ensure the long-term durability and efficiency of underwater photovoltaic systems. This section of the paper focuses on r addressing technical challenges posing a threat to such reliability.

Watertightness is a critical parameter for protecting electrical components and preventing short circuits. Encapsulation systems must be designed to withstand prolonged immersion while maintaining the transparency required for light transmission (Walters et al., 2015). On the other hand, while there is no specific test assessing the long-term submersion resistance of crystalline silicon PV, its EN EC6 1215:2005 qualification provide both a damp-heat test and wet leakage current test (Lanzafame, 2010). This provides a precise understanding of the capacity of a solar cell in underwater environment, i.e. 1000h resistance to humidity at a temperature of 85°C. Its internal protection (IP) – i.e. how well it is protected from dust and water infiltration- degree is

IP65, which is just below the IP7 required for immersed devices. It is fair to assume that reinforcing the junction box to reach that degree of IP is not an impossible endeavour (Lanzafame, 2010).

Corrosion poses a significant threat to metal components and interconnections, particularly in salt water. Kumar et al. (2020) highlight the need for corrosion-resistant materials and protective coatings to ensure system longevity, while Suzuki et al. (2015) demonstrated the drastic degradation of silicon PV cells that salt water and high voltage stress can cause.

Hydrostatic pressure, which increases with depth, can affect the structural integrity of PV modules (Liang, 2024). Stachiw (1980) highlights the importance of designing cells and encapsulations capable of withstanding the pressures expected at installation depth. No research has been done so far on the resistance of PV cells to pressure in underwater settings, but Shi et al. (2019) highlighted that a pressure higher than 1 bar applied on perovskite solar cells was detrimental to their efficiency.

Biofouling, or the accumulation of marine organisms on the surface of panels, can significantly reduce their efficiency. Ageev et al. (2002) showed the importance of developing biofouling prevention strategies, as it would otherwise reduce the efficiency of PV cells by 53% after only 30 days of operation.

Although water can provide natural cooling, temperature variations can still affect cell performance. Sargunanathan et al. (2016) highlight the importance of considering suitable cooling methods, even in an aquatic environment, to optimize efficiency.

One last limitation is the lack of standardized laboratory-based evaluation techniques, which means that most tests are either held in water tank or in-situ (Röhr, 2022). These in-situ measurement can only yield specific results that are not necessarily applicable to other locations. This makes inter-study comparison more challenging.

Finally, the main gap in knowledge highlighted by this paper is the absence of cost related analysis. While floating solar panels have been examined from a practical standpoint and the possibility of real-world implantation (Clemons et al., 2021), there has not been any research on the economic feasibility of an underwater solar farm.

2.4. Economic factors

Given the lack of existing designs for underwater solar farms and the limited cost analyses available, there is no literature on the overall feasibility of this technology. However, some assumptions can be made from other technologies. For instance, the design concept for a floating solar farm, as outlined by the World Bank Group in collaboration with the Energy Sector Management Assistance Program (ESMAP) and the Solar Energy Research Institute of Singapore (SERIS) (see Figure 5), can be adapted for an underwater solar farm.

Similarly, the economic analysis conducted by Brent et al. (2023) on the feasibility of floating solar power in Aotearoa New Zealand may be replicated. For instance, assumptions regarding inflation rates, operation and maintenance costs, and annual solar irradiance can be adapted to an underwater solar farm design. However, additional costs must be considered due to the unique nature of an underwater installation. The price of PV cells is a significant factor in the overall economic viability of the farm and varies considerably depending on the material used. Monocrystalline and polycrystalline silicon cells are the least expensive, with prices ranging from US$0.05/W to US$0.25/W depending on the time of the year (Feldman, 2023). In contrast, GaInP cells cost approximately US$4.85/W (Essig et al., 2017). The cost of PSC, as modelled by Mathews et al. (2020), depends on the scale of production and ranges from US$0.53/W to US$3.30/W. According to Kalowekamo et al. (2009), the cost of OSC can vary widely, with estimates between US$1.00/W and US$2.83/W. Finally, CdTe cells were evaluated at US$0.28/W for production in Southeast Asia (Smith et al., 2021).

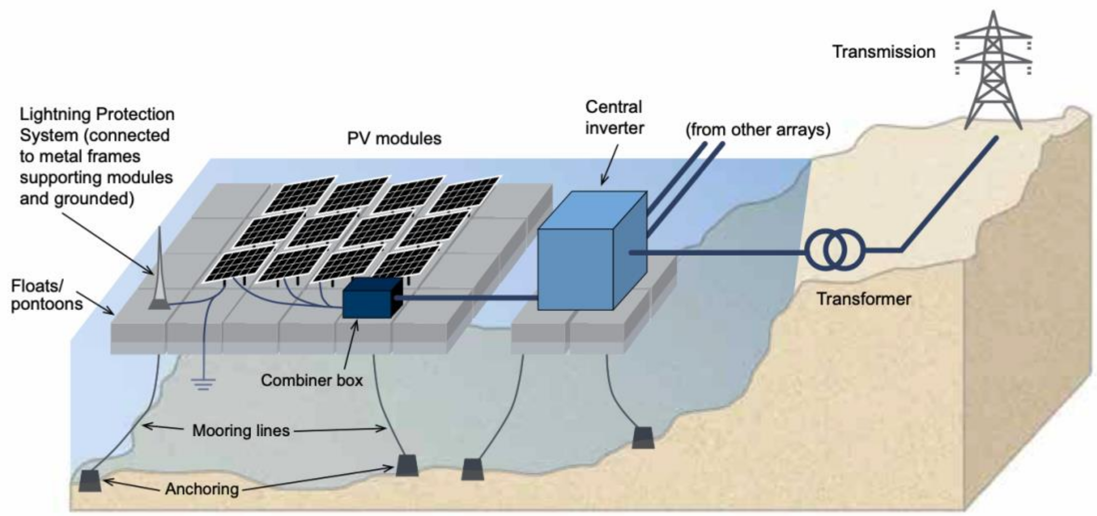


Figure 5. Conventional design of a floating solar farm
(Source: World Bank Group, ESMAP, SERIS, 2018)

Additionally, costs related to watertightness and maintenance due to increased water interaction are expected to be higher than those for a floating PV farm (Lanzafame et al., 2010). For example, for a 10MW floating solar array, operation and maintenance cost will be NZ$7.5/kWp/year compared to the NZ$1.5/kWp/year of a land-based array (Brent et al., 2023).

2.5. Review conclusions

To perform an economic viability assessment of an underwater PV farm, assumptions on the overall design of the plant must be made. In addition, the varying costs of PV cells must be considered, with additional expenses expected due to the underwater environment, such as watertightness and increased maintenance requirements.

This overview of the state-of-the-art in underwater PV technology highlights the potential for further research and identifies gaps that could be explored in future studies. A cost benefit analysis on the feasibility of underwater solar panel could determine if this new technology can become a viable component of the renewable energy landscape.

3. Research methods

The objective of this section is to present the methodology for the cost-benefit analysis (CBA). A CBA is a systematic framework for assessing the advantages and disadvantages of various alternatives by comparing their respective costs and benefits. The process begins by clearly defining the project or decision under consideration. Subsequently, all associated costs are identified, encompassing direct, indirect, tangible, and intangible costs, including but not limited to initial investment, operational expenses, maintenance costs, and any negative externalities. Likewise, all benefits are catalogued, covering direct, indirect, tangible, and intangible benefits, such as revenue generation, cost savings, increased efficiency, enhanced reputation, and positive externalities (Mishan, 2020).

Once all costs and benefits are identified, they are converted into monetary terms. This step often necessitates the use of estimates and assumptions, particularly for intangible factors. The next step involves calculating the net present value (NPV) by discounting future costs and benefits to their present value, thereby accounting for the time value of money. This enables a fair comparison between future and present values.

Following the NPV calculation, the net benefit is determined by subtracting total costs from total benefits. A positive net benefit indicates that the project or decision is economically viable, while a negative outcome suggests that the project may need to be reconsidered or abandoned. To ensure the robustness of the results, a sensitivity analysis is conducted by varying key assumptions and evaluating their impact on the outcome. This provides insights into the potential variability of the results.

In this study, the levelized cost of energy (LCOE) served as the primary metric to assess the economic potential of submerged photovoltaic solar panel (SP2) systems. The LCOE represents the NPV of the project's total costs divided by the NPV of the total electricity generated over the project's lifespan. The LCOE is computed using the following formula (Lai, 2017):

$$LCOE = \Sigma[(I_t + M_t)/(1+r)^{\,t}]/\Sigma(E_t/(1+r)^t\ )$$

Where I represents the initial capital investment or capital expenditure (CAPEX), M the annual operating and maintenance (O&M) costs, E the annual electricity generated, and r the discount rate. Among these variables, the CAPEX is the most significant factor.

Additionally, a sizing of debt was performed to determine the economic feasibility of an underwater solar farm (Raikar, 2020). The process analyses the optimal amount of debt a company can take on while ensuring the financial stability of the project. We used the debt service coverage ratio (DSCR) method, which calculates the cash flow available for payment using the following formula:

$$DSCR = \frac{Operating\ income}{Total\ debt\ (Principal + interest)}$$

The debt sizing provided two main outputs, the internal rate of return (IRR) and the equity breakeven period. The IRR represents the annualized rate of return of the investment. The higher this value, the more profitable the project. The equity breakeven period simply calculates how long it will take for the project to be return investment into profit. The shorter the period, the less risk there is for the investment.

3.1. Data assumptions and parameters

This study analysed different configuration for a SP2 plant, each with a different material for the PV panels: regular SI-cells, Dual junction GaInP cell, PSC, Cdte and OSC. Each of them was given a P-50 capacity factor, which is the median value at which the plant is expected to perform, based on their respective underwater efficiency reported in the literature. The counterfactual was a conventional land-based PV plant. Given that no such underwater farm currently exists in Aotearoa New Zealand, the analysis relied on data from similar systems elsewhere and adapted them to the specific context of this study. Most of the data consisted of quantitative primary sources, obtained from literature.

The following assumptions, largely drawn from Brent et al. (2023) due to the similarities between floating photovoltaic (FPV) and SP2 systems, were used to conduct the CBA:

- Offtake of 100%, meaning all generated electricity was exported to the grid.
- PPA agreement of NZ$80/MWh.
- DSCR ratio of 1.3x.
- A discount rate of 8%, based on the New Zealand Treasury's recommendations for energy infrastructure projects.
- Engineering, procurement and construction cost (see Table 1) of NZ1,98$/Wp for a 10 MWp system, according to NREL 2021 Renewable power generation cost in 2021 (2021), and adjusted to inflation (see Figure 6) using the New Zealand consumer price index (CPI) from the Reserve Bank of New Zealand (2025).
- Engineering, procurement and construction cost of 2,14$/Wp for a regular SP2 farm, using Miceli & Talavera's (2023) work on FPV as a baseline, and adjusting the assumption from a FPV to a SP2 farm (Table 1).
- For SP2 farms with dual junction panels, we add in the price per Wp of manufacturing the additional materials using available figures from literature (Cai, 2016; Habdul Adi, 2018; Smith, 2021).
- Electricity price inflation of 2%, based on the inflation forecast for New Zealand (IMF, 2024), which is a standard metric used in investment analyses.
- Annual degradation of the PV panels at 2.5% in the first year and 0.6% thereafter, based on industry standards (JA Solar, 2022). The impact of biofouling will be disregarded due to recent improvements in coating technology (Rajagopalan & Kiil, 2024).
- No specific data on O&M costs for SP2 systems is currently available; hence, for the purpose of this analysis, it is assumed that the O&M costs will be similar to those of FPV systems. Brent et al. (2023) estimates the O&M costs at 0.5% of the capital cost, excluding inverter replacement in year 12. In contrast, the equivalent O&M cost for a land-based PV array is NZ$1.5/Wp, with inverter replacement costing 7% of the initial engineering, procurement, and construction (EPC) expenses.
- Operating cost inflation of 2%, based on the electricity generation sector's assumptions in New Zealand (John Culy Consulting, 2019).
- A 30-year asset life, consistent with the performance warranty of PV modules (JA Solar, 2022).
- Efficiency loss of 2.5% for SP2 farms due to the necessity of keeping the panels flat (Figure 7).

The assumptions and initial parameters are summarized in Tables 2 and 3.

Table 1. Cost breakdown of LPV farm and conversion to FPV and SP2

NREL Cost Categories	LPV (USD/Wdc)	FPV (USD/Wdc)	SP2 (USD/Wdc)	IRENA Cost Categories
EPC/Developer Profit	0.08	0.07	0.07	Margin
Developer Overhead	0.07	0.07	0.07	Margin
Contingency	0.03	0.06	0.06	Financing costs
Sales Taxes	0.04	0.04	0.04	Financing costs
Shipping/Handling	0.02	0.02	0.02	Racking and mounting; Mechanical installation
Permitting, Inspection, Interconnection	0.04	0.05	0.05	Inspection; Permitting
EPC Overhead	0.07	0.08	0.08	Margin
Install labor & equipment	0.12	0.06	0.06	Safety and security; Monitoring and control; Racking and mounting; Mechanical installation
Electrical Balance of system	0.12	0.1	0.1	Cabling/wiring; Grid connection; Electrical installation
Structural Balance of system	0.11	0.37	0.24	Racking and mounting; Mechanical installation
Inverter	0.04	0.04	0.04	Inverters
Module	0.33	0.33	0.33	Modules
Total	1.07	1.29	1.16	

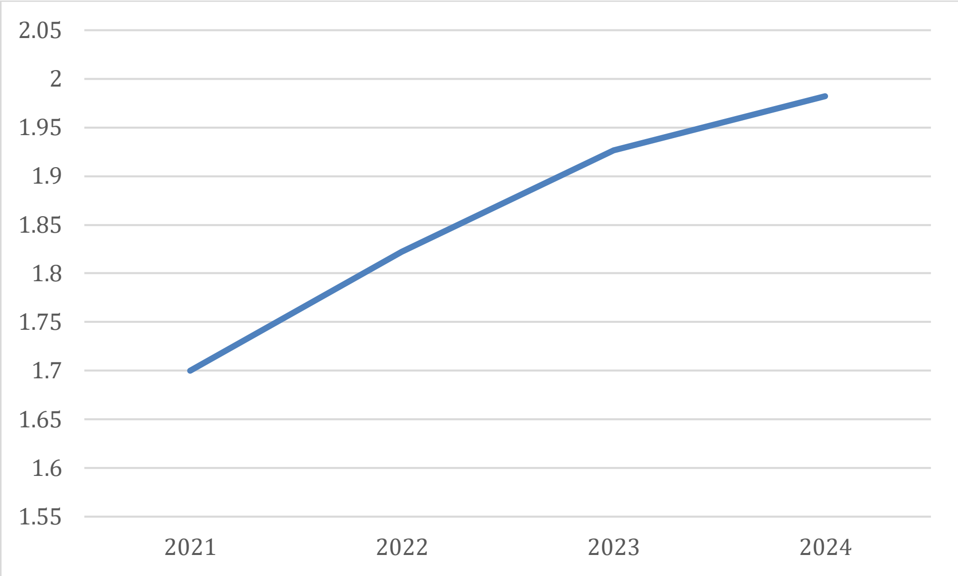


Figure 6. LPV CAPEX (NZ$/Wp) for a 10MW farm adjusted to inflation

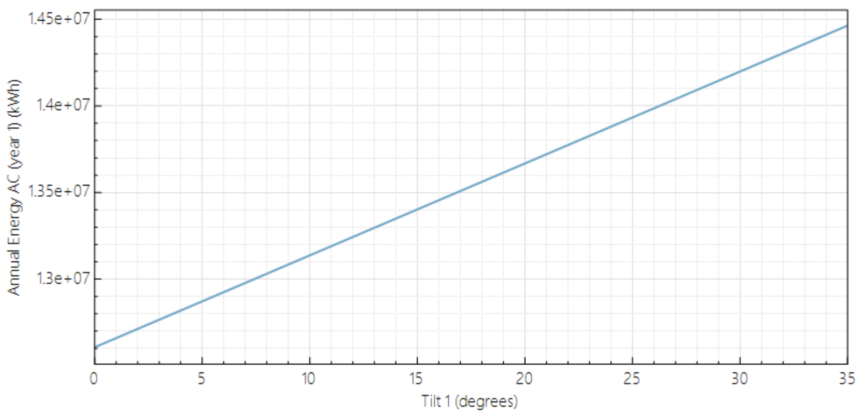


Figure 7. Energy generation difference between flat and optimal tilt angle

Table 2. Initial parameters of the debt sizing

Parameter	Value	Unit
Plant Capacity	10,0	MW
Capacity Factor	Variable (See Table 4)	%
Operating Expenses	Variable (See Table 4)	NZ$/kW-Year
PPA Price (year 1)	$80.00	per MWh
PPA Escalation Rate	2.0%	%
Inflation Factor	2.0%	%
Sizing DSCR	1.30x	Ratio
Interest Rate	8.0%	%
Hours in Year	8760	Hours
CAPEX	Variable (See Table 3)	NZ$/kW
CRF	9%	%

Table 3. Initial variables of the CBA

	Efficiency	Efficiency lost to tilt angle	CAPEX (NZ$/kW)	O&M costs (NZ$/kW-Year)
Counterfactual	20%	0	1 980.00	$1.50
Silicon	22.50%	2.50%	2 140.00	$10.70
PSC	42.10%	2.50%	2 800.00	$14.00
CdTe	24.10%	2.50%	2 620.00	$13.10
OSC	25.6%	2.5%	3 870.00	$19.35
GaInP	55%	2.5%	16 650.00	$83.25

Solargis (2021) provided long-term yearly averages of the solar irradiance in many areas of Aotearoa New Zealand. It was used in this study to estimate the suitability of different areas for a SP2 farm. Consistent with the findings of Brent et al. (2023), the Maraetai Dam was selected as the site for this analysis. It provides both strong global horizontal irradiance and is located near impactful node on the grid, close to cities and other cluster where demand is important (Brent et al., 2023).

Once all the costs and benefits related to the farm were added, the other benefits associated with moving the plant from the land to water were also studies. The most prominent was the continuation of livestock farming. Using the Hawke's Bay airport 10MW solar project as a reference, it was assumed that at least 15 ha of space is available for farming. In the region around the Maraetai Dam, most of the land is used for dairy farming (Vannier et al., 2022). The dairy sector contributes to NZ$11.3b per year to the Aotearoa New Zealand economy (Sense Partners, 2023), or NZ$6.6k per hectare. The export benefit from dairy is NZ$25.7b a year (Sense Partner, 2023), or NZ$15.1k per hectare. Additionally, since in Waikato region there is on average 2.7 cows per hectare and 120 cows per workers (DairyNZ, 2023), a single job paid at the average wage of 80k NZ$/year would be kept (Harris, 2023). The overall benefit should therefore range between NZ$189k and NZ$306.5 per year for a 10MW farm. This cashflow will be injected yearly as an added revenue to the farm and indexed to inflation following the previous assumptions.

4. Results and discussion

Tables 4 and 5 show the result of the analysis. The detailed breakdown of the analysis is available in the Supplementary Material. The sensitivity analysis provided on Table 6 examines how changes in Capex and Efficiency impact the LCOE for the different technologies.

Table 4. Comparison between LPV and SP2 farms

	Equity breakeven period (Years)	IRR	LCOE ($/MWh)
Counterfactual	16.54	5.22%	101.24
Regular SP2 (Si-panels)	19.95	3.42%	114.61
PSC	9.89	9.76%	76.12
CdTe	22.76	2.25%	129.92
OSC	0.00	-0.42%	179.44
GaInP	0.00	-3.07%	339.69

Table 5. Comparison between LPV and SP2 farms when considering farming benefit

	Equity breakeven period (Years) (lowest - highest)		IRR (lowest – highest)		LCOE ($/MWh) (lowest – highest)	
Counterfactual	16.54		5.22%		101.24	
Regular SP2 (Si-panels)	15.92	14.17	5.58%	6.79%	103.82	97.11
PSC	9.07	8.63	10.87%	11.53%	70.64	67.24
CdTe	18.71	16.88	4.01%	4.99%	119.93	113.72
OSC	26.70	24.38	0.93%	1.68%	170.10	164.30
GaInP	0.00	0.00	-2.69%	-2.46%	335.58	333.02

Table 6. LCOE variation for +/- 5% variation of Capex and Efficiency

LPV		Silcon		PSC		CdTe		GaInP		OSC	
CAPEX +/- 5%	**LCOE**	**CAPEX +/- 5%**	**LCOE**	**CAPEX +/- 5%**	**LCOE**	**CAPEX +/- 5%**	**LCOE**	**CAPEX +/- 5%**	**LCOE**	**CAPEX +/- 5%**	**LCOE**
0%	101.24	0%	114.60	0%	76.12	0%	129.92	0%	339.69	0%	179.44
-5%	96.22	-5%	108.88	-5%	73.21	-5%	124.61	-5%	337.51	-5%	174.48
5%	106.26	5%	120.33	5%	79.03	5%	135.23	5%	341.87	5%	184.40
Eff. +/- 5%	**LCOE**	**Eff. +/- 5%**	**LCOE**	**Eff. +/- 5%**	**LCOE**	**Eff. +/- 5%**	**LCOE**	**Eff. +/- 5%**	**LCOE**	**Eff. +/- 5%**	**LCOE**
0%	101.24	0%	114.61	0%	76,12	0%	129,92	0%	339.69	0%	179.44
-5%	106.57	-5%	120.64	-5%	80.12	-5%	136.76	-5%	357.57	-5%	188.89
5%	96.42	5%	109,15	5%	72.49	5%	123.76	5%	323.51	5%	170.90

4.1. Discussion

This study shows that the SP2 technology, in most cases, perform worse than a conventional land-based solar farm. This result was to be expected, as it is influenced by only two variables: the farm efficiency and its upfront costs. Although SP2 farms have higher potential energy output due to better efficiency, their performance is hindered by the need to keep the panels flat. On the other hand, the higher upfront costs drive the LCOE up, especially in the case of dual junction panels such as CdTe or GaInp. This results in farms that are more expensive to build and maintain while not compensating that weakness with a sufficient increase in electricity production. By either improving the efficiency of SP2 farms or reducing the CAPEX associated with new materials (the latter being more likely) this technology could eventually compete with land-based solar farms.

For instance, when considering the long-term for the manufacturing cost of GaInP cells presented in the work of Abdul Hadi et al. (2018), the LCOE for GaInP drops to 95,48 $/MWh (see Table 7), which would make it a great substitute to LPV. It is also worth noting that, due to their lower initial costs, the SP2 farm fares better than the FPV farm, whose LCOE range between 176 $/MWh and 237 $/MWh per MWh (Brent et al., 2023).

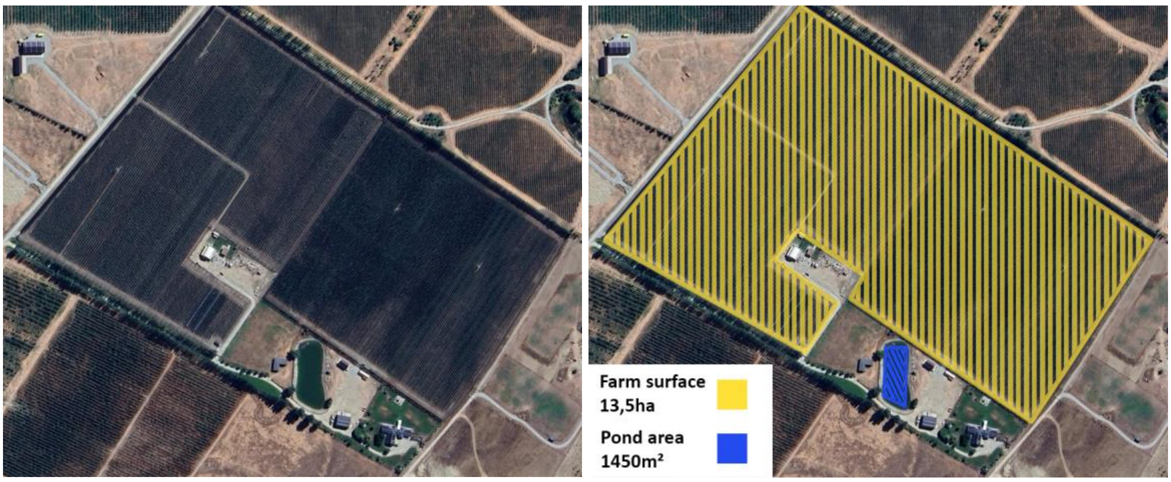
Table 7. LCOE with long-term scenario cost for GaInP

Equity breakeven period (Years)	IRR	LCOE ($/MWh)
13,99	6,73%	95,48

However, when the other benefits of underwater solar farm are considered, such as the continuation of cow grazing or farming, the gap narrows. Depending on the assumptions, the silicon SP2 farm manages to either equal or surpass the counterfactual with a LCOE as low as 97.11 NZ$/MWh. Similarly, while the outcomes show that SP2 is not necessarily suitable for large scale farms, the electricity produced is still at a lower price than what is offered on the grid. Therefore, farmers with access to water areas, such as irrigation ponds, could still make use of the technology by placing a few underwater solar panels.

4.1.1. Case study

A cherry farm located near Cromwell, Central Otago, with access to 1450 m^2 of still water was selected to conduct this complementary analysis (see Figure 8). This farm owns 13.5 ha of land and consumes up to 260 MWh a year, or 19 MWh/ha. When buying from the grid, this would amount to NZ$55 475 a year (MBIE, 2024). Using a simple formula (NREL, 2024) to calculate the required capacity of the SP2 system (Table 8) and using its System Advisor Model (SAM) to determine the size of the array (Figure 9), it is estimated that only 750m^2 or 50% of the pond area would be required to supply the cherry farm's required electricity. This additional source of energy would generate 260 MWh a year for a cost of only NZ$26,322.40, resulting in more than NZ$20 000 of saving a year without compromising on farmable areas.



Figures 8. Cherry farm (left) and size of the areas studied (right)

Table 8. Nameplate capacity required for the array

Parameter	Value
Required energy (MWh-Year)	260
Hours in a year	8760
Capacity	20%
Minimum nameplate capacity (kW)	148,40

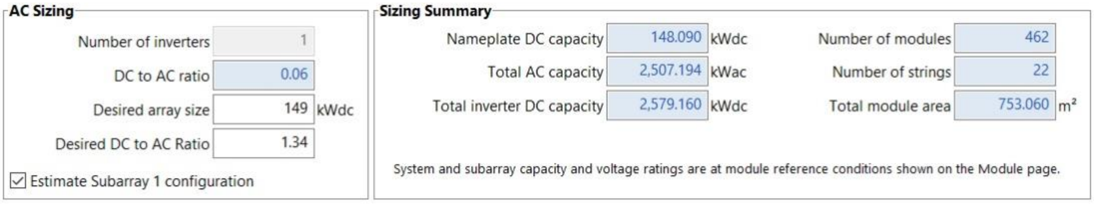


Figure 9. Configuration of the SP2 system for the cherry farm

Therefore, small-scale use of the SP2 technology can still be favourable, allowing to lower the cost associated with electricity consumption while having no impact on the farming activity due to the location of the panels.

5. Conclusion and recommendations

This study provides a comprehensive economic analysis of SP2 farms, assessing their feasibility compared to LPV and FPV systems. The findings indicate that while SP2 technology offers certain advantages, such as improved cooling and efficiency gains, these benefits are largely offset by high capital expenditures, increased maintenance costs, and the technical limitations of underwater deployment.

One of the key challenges identified is the economic viability of SP2 farms. The CBA demonstrates that, under current conditions, SP2 systems generally result in a higher LCOE than conventional LPV. The additional costs associated with waterproofing, corrosion resistance, and biofouling prevention make the initial investment significantly more expensive. While submerged panels may benefit from a cooling effect that enhances efficiency, this advantage is not sufficient to compensate for the higher CAPEX and operational costs.

Despite these challenges, SP2 technology shows potential for niche applications. While large-scale SP2 farms may not yet be competitive with land-based solar installations, they could be viable in specific cases where land availability is limited or where water-based solar generation would allow for dual land use. The study highlights, for instance, how SP2 systems could be integrated into agricultural settings without reducing farmable land, providing an additional source of renewable energy for farmers while maintaining traditional livestock or crop production.

Material selection plays a crucial role in determining the economic feasibility of SP2 farms. The analysis compares various solar cell materials, showing that while advanced materials such as GaInP and CdTe perform well underwater, their high production costs currently hinder commercial adoption. On the other hand, silicon-based SP2 panels, though still more expensive than land-based alternatives, appear to offer the most balanced trade-off between efficiency and cost.

A sensitivity analysis suggests that reductions in manufacturing costs, particularly for newer solar cell materials, could significantly improve the competitiveness of SP2 technology. If production costs decline—especially for high-efficiency materials like GaInP or OSC—SP2 could emerge as a viable option for renewable energy generation. Further research into enhanced corrosion resistance, biofouling mitigation, and large-scale deployment strategies could also improve the economic outlook of SP2 farms in the long run.

5.1. Recommendations

While this study provides a foundational analysis of the economic feasibility of SP2 technology, several areas require further investigation to refine its potential for commercial deployment.

One critical area for future research is the long-term durability of submerged solar panels. More studies are needed to assess the degradation rates of different materials in underwater environments, particularly under varying conditions such as saltwater exposure, biofouling accumulation, and hydrostatic pressure. Additionally, research into innovative protective coatings and encapsulation techniques could help extend the lifespan of SP2 panels and reduce maintenance costs.

Another important avenue for exploration is the optimization of SP2 system design. While this study assumed a flat-panel configuration due to underwater placement constraints, alternative designs that allow for dynamic panel orientation could maximize sunlight capture and improve efficiency. Computational modelling and experimental testing should be conducted to determine the most effective structural arrangements for submerged solar arrays.

Economic modelling should also be expanded to include real-world pilot projects. While this study relied on financial projections based on existing data, future research should incorporate empirical data from SP2 test sites to validate cost assumptions and efficiency estimates. Studies comparing SP2 performance in different aquatic environments—such as freshwater lakes, coastal waters, and reservoirs—would provide valuable insights into site-specific feasibility.

Lastly, further research is needed to assess the ecological impact of submerged solar farms. While SP2 has the potential to be a sustainable energy solution, its effects on aquatic ecosystems remain largely unexplored. Long-term monitoring of marine biodiversity, water chemistry, and sedimentation patterns around SP2 installations would help determine whether these systems can be deployed at scale without causing environmental harm.

By addressing these research gaps, future studies can build upon the findings of this thesis and help pave the way for SP2 technology to become a viable addition to the global renewable energy portfolio.

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