Sustainable Energy Technologies and Assessments 57 (2023) 103284

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

An assessment of the economic feasibility of the floating PV technology in Aotearoa–New Zealand

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A R T I C L E I N F O

Keywords:
Floating PV
Economic performance
Feasibility
Sustainability

A B S T R A C T

Electricity generation from utility-scale solar facilities is projected to grow to between 5 and 16 TWh by 2050 in Aotearoa–New Zealand. The floating photovoltaic (FPV) technology is considered a viable option for the country, because of the good solar resource at existing hydropower schemes. This paper aims to inform the understanding of the economic feasibility of FPV systems through the analysis of specific cases – Maraetai Dam and Lake Tekapo. To do so, the solar resource and FPV outputs are obtained through the modelling of Solargis and using industry standard technical specification. As well as the normal uncertainties associated with (potential) FPV performance evaluations, the influence of water temperature is also considered. The overall FPV output is estimated to be between 1,115 and 1,497 kWh/kWp. Using available Engineering, Procurement and Construction (EPC) costs, the levelized cost of energy (LCOE) metric, for a 10 MW installation, is determined to be between NZ $176 and NZ$237 per MWh, with total electricity generation over 25 years between 263 and 353 GWh. In order to reach the required LCOE value of less than NZ$100/MWh for utility scale generation, the EPC costs will have to be reduced by a factor of 2 to around NZ$1,500/kWp.

Introduction

Aotearoa–New Zealand has a highly renewable-based electricity system, with 84 per cent of electricity generated from renewable sources [1]. The renewable sources are primarily hydro, geothermal, and wind, with limited sectoral growth since 2014 (see Fig. SI-1 in the Supporting Information).

Aotearoa–New Zealand is undertaking its transition to a net zero carbon emissions economy by 2050, as envisaged through the Climate Change Response (Zero Carbon) Amendment Act [2]. To achieve the transition, the Government has set an aspirational goal of 100 per cent renewable electricity by 2035, through its Renewable Energy Strategy, with a range of work programmes to achieve that being underway [3]. In line with the Government's strategy, the majority of proposed generation capacity is from renewable sources, with most projects capitalising on the wind resource of the country (see Fig. SI-2 in the Supporting Information); the sum total of potential new wind generation capacity is roughly 2600 MW, over 45 per cent of current national hydro generation power capacity [1].

There is also a significant focus on electricity generation from Aotearoa-New Zealand's abundant solar resource. Accordingly, the country has seen growth in the uptake of solar photovoltaic (PV) systems over the past five years, though from a low base, with an increase of just under 30 per cent in 2018 and 2019, to a total installed capacity of over 130 MW [4]. As shown in Fig. SI-3 in the Supporting Information, the residential sector has been the key driver for solar PV installations, accounting for over 70 per cent of installed capacity at the end of 2019. The rate of solar uptake by other market segments – small and medium enterprises, commercial, and industrial – increased at an even higher or similar rate to residential use, but from a much lower base. Nevertheless, an addendum to the Te Mauri Hiko scenarios of Transpower, the national transmission system operator [5], projects solar technologies to generate between 10 and 32 TWh of electricity (of a total of 88 TWh) by

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https://doi.org/10.1016/j.seta.2023.103284
Received 11 June 2020; Received in revised form 31 October 2022; Accepted 9 May 2023
Available online 17 May 2023

Nomenclature

DIF	Diffuse horizontal irradiation
DNI	Direct normal irradiation
EPC	Engineering, procurement and construction
FPV	Floating photovoltaic
GHI	Global horizontal irradiation
GIS	Geographic Information System
GTI	Global tilted irradiation
kW	Kilowatt
kWh	Kilowatt hour
kWp	Kilowatt peak
LCOE	Levelised cost of energy
MW	Megawatt
MWh	Megawatt hour
MWp	Megawatt peak
NPV	Net present value
O&M	Operating and maintenance
OPTA	Optimal tilt angle for GTI
PV	Photovoltaic
PVOUT	Photovoltaic electricity output
TEMP	Temperature at 2 m
TW	Terawatt
TWh	Terawatt hour
W	Watt
Wp	Watt peak

2050, of which at least half will be from distributed solar PV, and the remainder from utility-scale facilities. To this end a number of utility-scale PV projects are underway, such as the solar farm of Refining NZ [6], a community solar farm on the Kāpiti Coast [7], and the floating PV array at Watercare in Auckland [8].

The latter is the focus of this paper, with the aim to better understand the economic feasibility of such utility-scale projects in the Aotearoa–New Zealand context.

Increasing uptake of floating photovoltaic systems

Floating photovoltaic (FPV) systems are seen as an opportunity for scaling up solar generating capacity around the world, especially in regions with competing uses for available land [9]. A number of benefits with FPV systems are cited [10]:

- For lake or reservoir owners:
  - o Reducing costs for waterbody maintenance, due to decreased algae growth;
  - o Reducing rates of water evaporation and increasing available water for other uses; and
  - o Converting potentially underused space into areas that allow for revenue-generating use.
- For solar PV developers:
  - o Lower land acquisition and (potentially) site preparation costs;
  - o Gaining potential system efficiency and production due to the temperature-regulating effect of water and the decreased presence of dust;
  - o Increasing panel density for a given area (larger installed capacity per unit area) due to lower tilt angles; and
  - o Power system benefits and reducing capital costs when co-located with hydropower.

The latter is of particular interest, especially in the case of large hydropower sites that can be flexibly operated [9]; to boost the energy yield of such assets, and manage periods of low water availability, which is a key issue for the national grid of Aotearoa–New Zealand, in dry years [11].

The benefits, and opportunities, have seen an exponential growth in the global cumulative installed FPV capacity (see Fig. SI-4). The cumulative installed capacity is now in excess of 1.1 GWp, the same milestone that ground-mounted PV reached in 2000 [9]. It is expected that FPV could advance as rapidly as ground-mounted PV in the coming years. Nevertheless, the development of grid-connected hybrid systems that combine hydropower and FPV are still at an early stage [9], and requires further context-specific investigations [12]. The contribution of this paper is then to assess the economic feasibility of the FPV technology for specific Aotearoa–New Zealand cases.

The FPV technology and the associated costs from literature

The World Bank Group, in collaboration with the Energy Sector Management Assistance Program (ESMAP) and the Solar Energy Research Institute of Singapore (SERIS), provide a comprehensive overview of typcial FPV systems and the related components – see Fig. SI-5 [9].

In general, FPV systems are similar to ground-mounted PV systems, with the only difference being that the PV modules and arrays are mounted on floating platforms. Combiner boxes on the platforms gather the direct current (DC) electricity that the PV modules generate and inverters convert the DC to alternating current (AC). In contexts where the floating platforms can be close to shore, the inverters may be placed on land. Otherwise, both central or string inverters on specially designed floats are typically used. Integral to any floating PV installation is the necessary anchoring and mooring of the platforms, and the detailed design for specific sites are provided in literature [12–14].

From a cost perspective, for FPV systems in the order of 10 MWp, the literature indicates a cost of around NZ$3/Wp[1] [14]. For very large systems, the only cost reported in literature is for a 150 MW system in China, at less than NZ$2/Wp [15]. The World Bank Group et al. [16] project that, in the near future, for a system size in between – of 50 MW – the cost could be as low as NZ$1.16/Wp. However, again, further context-specific assessments are required [12].

Methods to assess the economic feasibility of the FPV technology

To assess the economic feasibility of FPV systems in the New Zealand context, the solar resource was first determined at existing, selected hydropower schemes. The solar resource of Aotearoa–New Zealand [17] has been evaluated in collaboration with Solargis [18], a widely used service provider to estimate solar yield, which has also established the Global Solar Atlas with support of the World Bank Group, and with funding from the Energy Sector Management Assistance Program [19]. The solar radiation was calculated by numerical models, which are parameterized by a set of inputs characterizing the cloud transmittance, state of the atmosphere, and terrain conditions. The solar resource was then derived from algorithms that use the original 10-minute and 30-minute time series of satellite images, and auxiliary atmospheric datasets; as GIS raster data layers, which, apart from the GHI (kWh/m^2) and DNI (kWh/m^2), comprise of: GTI – Global Tilted Irradiation at optimum angle (kWh/m^2), DIF – Diffuse horizontal irradiation (kWh/m^2), OPTA – Optimum Angle for GTI (°), TEMP – Temperature at 2 m (°C), and PVOUT – Photovoltaic Electricity Output (kWh/kWp) [17].

Figs. 1 and 2 provide an overview of the solar resource, with the

[1] In the last quarter of 2022, the New Zealand Dollar (NZ$) averaged at US $0.59.

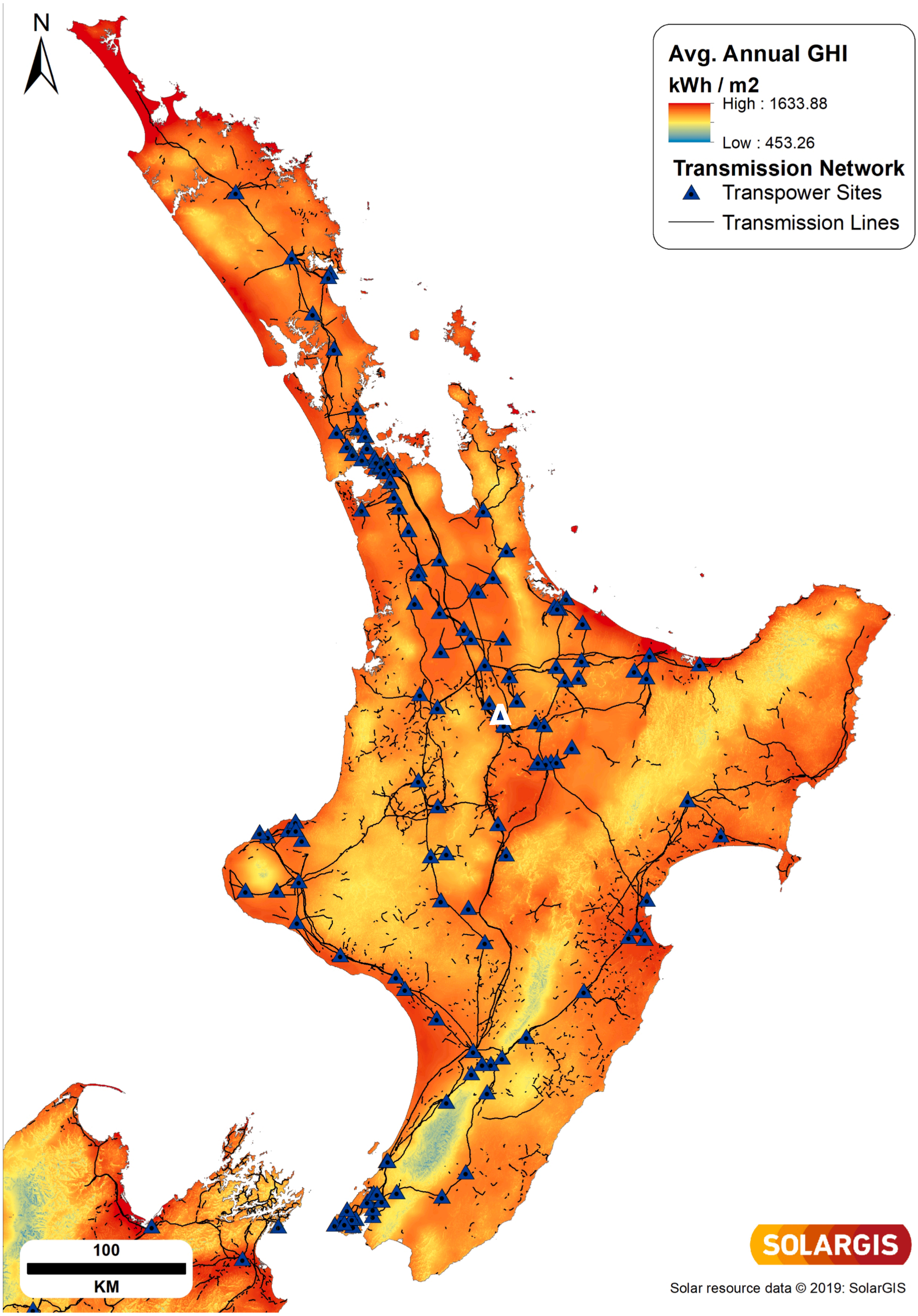

Fig. 1. Long-term average of annual sum of GHI, period 2007–2018 [kWh/m^2], for the North Island [17].

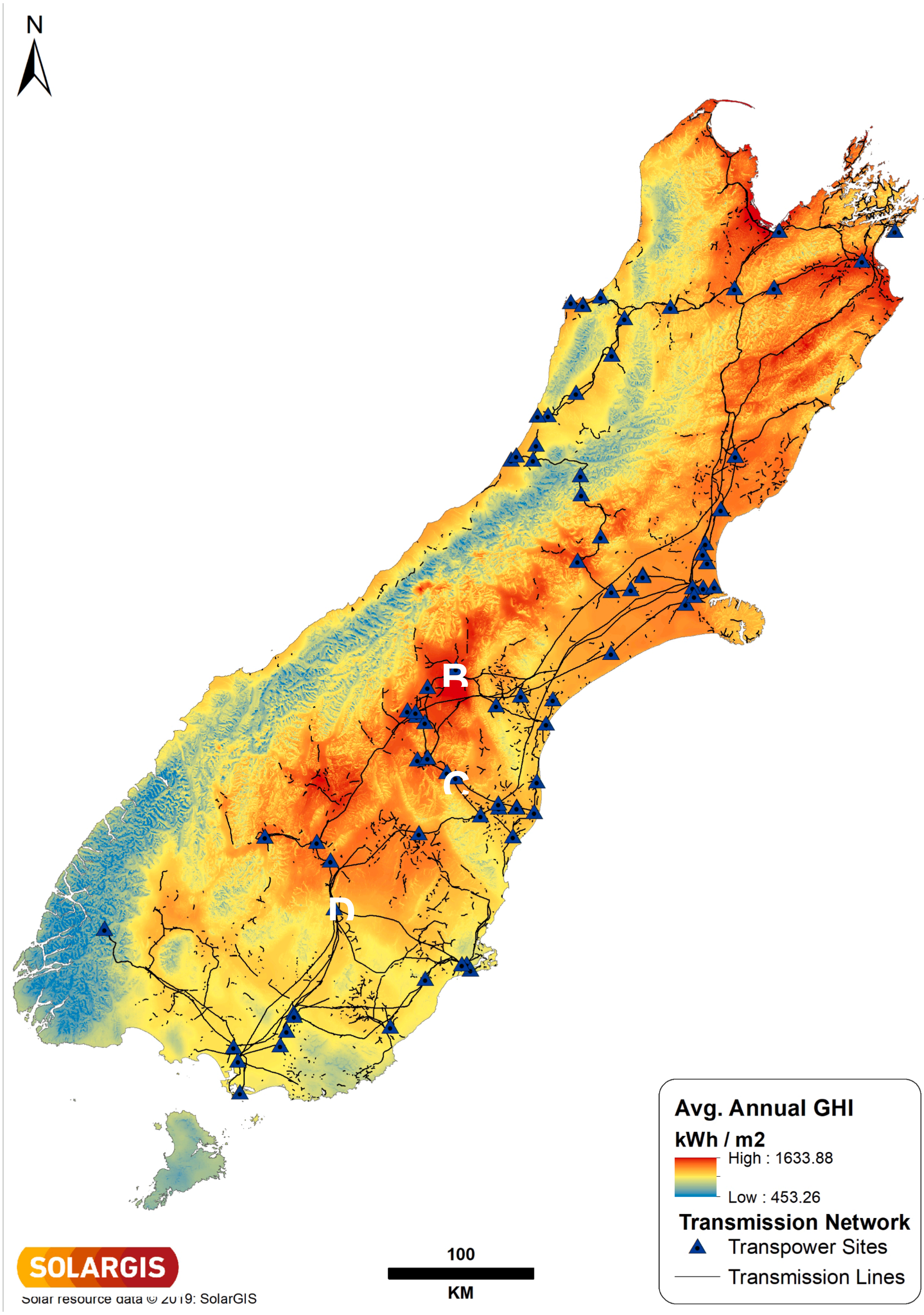

Fig. 2. Long-term average of annual sum of GHI, period 2007–2018 [kWh/m^2], for the South Island [17].

details provided in [17], and include the transmission system supplied by the Transpower [20], the government entity that owns and operates the national grid.

Ten hydropower sites with large surface areas suitable to accommodate utility-scale FPV systems without significant environmental impacts, and with the potential asset capacity to hybridise the existing electricity generation operations with FPV, were selected – see Table 1. The table provides the solar resource – average annual global horizontal irradiance (GHI) from 2007 to 2018 – on the lake or dam, and the distance between the nearest hydro power station infrastructure and a suitable FPV location on the edge of the lake or dam. Techno-economic feasibility analyses in literature [13,14] indicate that a good solar resource and the distance from existing power generation infrastructure are crucial from a Levelised Cost of Energy [22] perspective. Therefore, only sites with a GHI of over 1300 kWh/m^2 and a power station/lake distance of less than 1 km were considered technically and economically feasible.

Eight of the sites that were assessed have an average annual GHI of over 1300 kWh/m^2. Of these, three sites have distances between the power stations and suitable locations on the lakes of less than 1 km. These three sites have GHI differences of less than 5%, which is not deemed significant [17]. Only one site – Maraetai – is on the North Island, and less remote. The proximity to the main economic clusters of the country and with higher nodal prices in the wholesale market on the North Island [21] may make this site more feasible. The orientation of the lake (see Fig. SI-6) also means that an FPV installation can be made closer to the power station, which is only 300 m from the lake shore, with other Transpower infrastructure in also relatively close vicinity. This site was therefore selected for further analysis. In addition, Lake Tekapo (Fig. SI-7) was also considered, because it has the highest solar resource of the ten hydropower sites, and the power station/lake distance is only slightly more than 1.7 km, which also may make this site more feasible for an FPV installation.

For these two case study sites the potential outputs, in terms of generated electricity, were evaluated by first considering convention ground-mounted PV systems at the sites, and then incorporating parameters associated with FPV systems. The Levelised Cost of Energy metric [22], with sensitivity analyses, was finally utilised to assess the economic feasibility.

Potential FPV output at Aotearoa–New Zealand hydropower schemes – Maraetai Dam and Lake Tekapo

Conventional ground-based PV system at Maraetai Dam, and Lake Tekapo

The specific solar resource, meteorological information, and potential PV electricity production at Maraetai Dam (-38°21′31″, 175°46′29″) and Lake Tekapo (-43°59′16″, 170°29′19″) were obtained from Solargis for the 2018 calendar year, as a half-hour time series. The potential electricity production was also analysed with the models and algorithms provided through the Solargis Prospect tool [23] with a time representation from 2007 to 2018. The performance analyses of PV systems using the Solargis models and algorithms have shown a good correlation with measured performances at specific sites across the globe [24], and the associated Prospect tool is widely used in the solar sector, by both industry and researchers. A Solargis report of the solar PV potential at the Maraetai site is provided as supplementary material to this paper, and the methodologies that underpin the analyses are available in the public domain [25,26].

The initial estimate of the potential electricity production considered a typical ground-based fix-mounted system on levelled ground next to Maraetai Dam, using commercially available crystalline silicon PV modules that are well-ventilated, with no energy storage, but with the necessary balance of plant, such as a centralized high-efficiency inverter (97.8%) and a high-efficiency transformer (0.9% loss). The azimuth (0°) and optimal tilt at the two latitudes (32° and 38°) were taken as homogenous across all the PV modules, with monthly soiling losses of up to 3.5%. The system availability was taken as 99.5%, with additional losses, namely: DC cabling (2%), DC mismatch (0.3%), and AC cabling (0.5%).

For the 2018 calendar year, the total PV output on Maraetai Dam is 1208 kWh/kWp, which is 6% lower than the twelve-year average (from 2007 to 2018) of 1286 kWh/kWp, given a slightly less GHI resource of 1330 kWh/m^2 (−4%) and a GTI of 1531 kWh/m^2 (−1%); see Table SI-1. The PV output is in the order of 18% lower than the estimated twelve-year average of 1570 kWh/kWp for a similar system next to Lake Tekapo. The overall uncertainty of the output values is estimated to be ± 4.0 to ± 5.5% due to the uncertainty associated with the solar resource data [27].

FPV system on Maraetai Dam, and Lake Tekapo

An FPV system was considered using modules assembled on plastic floating pontoons, oriented towards the equator. The Solargis Prospect tool [23] includes the option to analyse such systems, with some differences to conventional ground-based systems (see the full report for Maraetai Dam as supplementary material): the modules have a (potentially) lower operational temperature due to cooling by evaporation of the surface water, although this was, at first, assumed to minimal due to the low ambient temperatures at the site; a higher mismatch between modules in a string (wave-induced mismatch), with losses due to DC cabling (2.5%), DC mismatch (6.5%), and AC cabling (2%); higher expected soiling due to bird droppings (up to 6% losses); and string inverters (96.4% efficiency) and a distribution transformer (1% loss) are included, with a lower expected availability of the system – at 98% – due to a harsher environment, with a higher probability of occurrence of various types of failure.

The PV output on Maraetai Dam reduces by 13% to just over 1115 kWh/kWp (see Table SI-2) for a twelve-year average, and just over 1360 kWh/kWp in the case of Lake Tekapo. This is largely attributed to the reduction of tilt angle – from the optimal tilts of 32° and 38° to 17°, which is typically observed for these kinds of installation [28]. Smaller

Table 1
Hydropower sites for potential FPV hybridisation in New Zealand, from north to south.

Site	Annual GHI kWh/m^2	Optimal tilt angle °	Nearest power station	Station/Lake distance km	Map location
Lake Arapuni	1403.7	32	Arapuni	> 4.8	
Maraetai Dam	1378.6	32	Maraetai	< 0.3	**A** (Fig. 1)
Lake Taupo	1478.0	32	Aratiatia	> 10.5	
Lake Tekapo	1503.2	38	Tekapo 'A'	> 1.7	**B** (Fig. 2)
Lake Pukaki	1425.2	37	Tekapo 'B'	> 1.5	
Lake Benmore	1425.1	38	Benmore	> 11.0	
Lake Aviemore	1418.7	39	Aviemore	< 0.3	**C** (Fig. 2)
Clyde Dam	1375.4	39	Clyde	< 0.5	**D** (Fig. 2)
Roxburgh Dam	1239.4	40	Roxburgh	< 0.3	
Lake Manapouri	972.9	36	Manapouri	< 0.3	

row spacing is usually considered necessary to reduce investment in pontoons and as such necessitates a smaller tilt angle to reduce inter-row shading effects – although this may be challenged by future pontoon designs. The uncertainty of the output values is, again, estimated to be ±4.0 to ±5.5% [27].

Output uncertainty due to the influence of water temperature

A major advantage of FPV systems is that the water typically lowers the temperature of the PV modules with consequent increase in panel efficiency. Ranjbaran et al. [12], from a review of literature, conclude that the efficiency of the modules can be enhanced by about 12% due to the lower operating temperature. However, they do note that more investigations are needed to understand the effects of geographical locations, and other factors. Impacts of temperature on panel efficiency is typically estimated using the temperature coefficient provided by the manufacturer. For a suitable double glass monocrystalline module, the temperature coefficient of the rated maximum power of a module is estimated to be −0.37%/°C [29].

Kamuyu et al. [30] developed a prediction model to understand the influence of water temperature and other atmospheric conditions on FPV performances. They established the following formula:

$$T_m = 1.8081 + 0.9282.T_a + 0.021.G_T - -1.2210.V_w + 0.0246.T_w \tag{1}$$

With T_m being the PV module temperature (°C), T_a the ambient temperature (°C), G_T the solar irradiance (W/m^2), V_w the wind speed (m/s), and T_w the water temperature (°C). From the validation of Kamuyu et al. [30], the formula overestimates the measured temperature by 4%. They further confirm that a 1 °C increase in T_m results in a 0.058% decrease in module efficiency, which corresponds with the Evans-Florschuetz efficiency correlation for typical silicon-based PV modules [31].

Recorded surface water temperatures are not readily available in the public domain for all water bodies in New Zealand. However, NIWA [32] installed a buoy monitoring station at the deepest site in Lake Taupo, which is approximate 50 km from Maraetai Dam, upstream on the Waikato River. In-situ water temperatures at a depth of 1 m were sampled and recorded in the global database of lake surface temperatures [33]. From 1995 to 2009 the surface temperature, in summer months, averaged 19.2 °C. Historic data over this period [34] indicate the surface temperature to fall to an average of 11.5 °C, similar to the temperature at a depth of 130 m. The seasonal variations in the surface temperature closely follow the recorded ambient temperatures (see Fig. SI-8), which indicates an incomplete vertical mixing of the water columns in the lakes of the Waikato region [34]. Over the 2018 year, a linear fluctuation of the water temperature was then assumed, between 19.2 °C on the warmest day (28 January) and 11.5 °C on the coldest day (3 July), as shown in Fig. 3.

Recalculating the PV output using the same methodologies [25,26] for the half-hour time series of the 2018 year, taking into account the temperature change of the modules and the associated efficiency gains, increases the total output by 4.9%, which is similar to the uncertainty associated calculated outputs [27]. Therefore, taking into account all of the uncertainties associated with the FPV systems, the PV outputs are estimated to be between 1115 and 1227 kWh/kWp for Maraetai Dam, and between 1360 and 1497 kWh/kWp for Lake Tekapo – although values on Lake Tekapo may be enhanced by the cool, glacial nature of inflows in this location. These PV outputs are before degradation of the PV modules, which is estimated to be between 0.8% and 2.5% in the first year, and 0.5% per year thereafter (see the supplementary material).

Economic feasibility of the FPV technology at New Zealand hydropower schemes

The Levelised Cost of Energy (LCOE) metric [22] was utilised to assess the economic feasibility of FPV systems, which is calculated by dividing the net present value (NPV) of total costs with the NPV of total electricity generated over the lifetime of the project, according to the following formula:

$$LCOE = \Sigma\left[(I_t + M_t)/(1+r)^t\right] / \sum (E_t/(1+r)^t \tag{2}$$

With I being the initial capital investment, or Engineering, Procurement and Construction (EPC) costs, M the yearly operating and maintenance (O&M) costs, E the yearly electricity generated, and r the discount rate.

The LCOE metric therefore has two key uncertainties, namely: the projected electricity that will be generated (as discussed in the previous section), and the cost of EPC. To address the EPC uncertainty a number of potential turnkey suppliers were identified and approached to obtain cost estimates. For smaller systems – 100 kWp – the turnkey cost is in the order of NZ$4/Wp. In the 1 to 10 MWp range, the cost reduces to around NZ$3/Wp, which is similar to what is reported in literature [14]. For this analysis, the installation of a 10 MW system, with an EPC cost of NZ$3/Wp, was therefore assumed before a sensitivity analysis was undertaken.

The other key parameters in the LCOE analysis, with initial

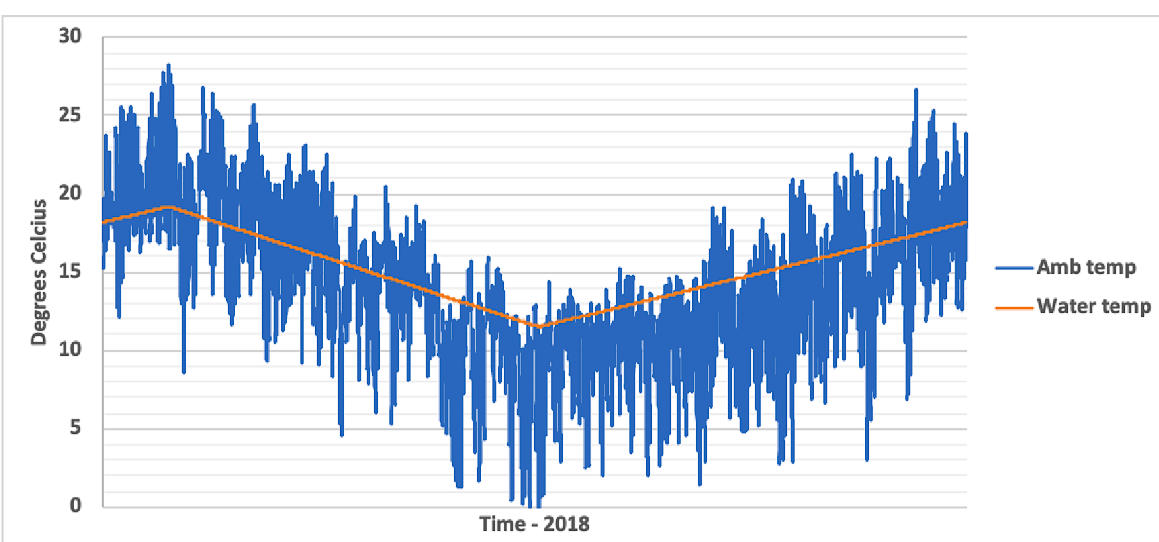

Fig. 3. Real ambient and estimated surface water temperature at Maraetai Dam.

assumptions, included:

- Offtake of 100%, i.e. all of the generated electricity is exported to the grid.
- Electricity price inflation of 2% – based on the inflation forecast for New Zealand [35], which is also widely used for investment analyses.
- Discount rate of 6% – based on the recommendation of the New Zealand Treasury [36] for (energy) infrastructure projects.
- Annual degradation rate of the PV panels at 2.5% in the first year of operation, and 0.5% thereafter – based on industry standards [37].
- O&M costs are estimated at 0.5% of the capital cost – based on current estimates for land-based PV systems [14]. For a 10MWp floating solar array, this is equivalent to an O&M cost of NZ$7.5/kWp/year – excluding inverter replacement in year 12 – compared to an equivalent cost of a land-based PV array of NZ$1.5/Wp [38]. Inverter replacement occurs at the end of the inverter warranty and costs 7% of the initial EPC.
- Operating cost inflation is 2% – based on the value assumed across the electricity generating sector in New Zealand [39].
- 25-year asset life in line with performance warranty of PV modules [37].
- For the counterfactual case for grid electricity, the following assumptions were used:
- Marginal electricity cost of NZ$0.08/kWh – based on the ICCC 'middle of road' scenario to achieve 93% electricity generation from renewables in 2035 [39]. This determines the O&M costs in equation (2) with no initial capital investment required.
- Same discount rate and project life assumptions as the FPV case.

This equates to a counterfactual LCOE over 25 years of NZ$96.6/MWh. Conversely, the FPV LCOE as per the above assumption for an FPV system on Maraetai Dam equates to between NZ$214.7 and NZ$236.3 per MWh, with the total electricity generated over the 25 years between 262.7 and 289.0 GWh. For a system on Lake Tekapo, the LCOE equates to between NZ$176.0 and NZ$193.7 per MWh, with total electricity generated over 25 years of between 320.4 and 352.6 GWh. Therefore, FPV systems in Aotearoa–New Zealand, for the assumptions used, are found to be between 1.8 and 2.5 more expensive than adding marginal generating systems to the grid.

Sensitivity analysis – EPC cost

The outcomes show the importance of reducing the uncertainty associated with the PV output, which has a linear effect on the calculated LCOE – 10% for the analysed cases. The next parameter with the largest effect – that can be substantially influenced – is the FPV system cost (see Fig. 4). In the figure, 'low irradiance FPV' refers to the low solar resource case at Maraetai Dam, and 'high irradiance FPV' refers to the high resource case at Lake Tekapo. The counterfactual LCOE can only be obtained if an EPC cost between the projected NZ$1.16/Wp of the World Bank Group et al. [16] and NZ$1.60/Wp is realised.

Sensitivity analysis – Tilt angle

As mentioned before, to reduce the investment requirement for the pontoon construction, a lower tilt angle is typically used. If future pontoon designs can accommodate higher tilt angles similar to ground-mounted systems, without significantly increasing the construction costs, the LCOE could reduce by 13% to NZ$152.6/MWh, considering a high solar resource case at Lake Tekapo (see Fig. 5). The counterfactual LCOE can then be obtained if an EPC cost between NZ$1.30/Wp and NZ$1.70/Wp is realised, which is not too significant.

Sensitivity analysis – Network and other non-wholesale pricing

The cost of electricity to consumers includes metering, network charges, tax and retailer margin, and it is estimated that the cost of electricity generation makes up 32% of an average electricity bill [40]. Some of these charges are fixed, such as fixed network charges depending on the connection voltage, whilst others are variable.

If FPV systems are targeted at behind the meter installations, then it can offset some of these variable charges and as such is comparable to a higher counterfactual LCOE. As shown in Fig. 6, moderate variable charges mean that FPV can be competitive against counterfactual variable charges of $40/MWh within the reported EPC costs. For reference, the variable charge for a high energy user in a high cost area of the distribution network serving Lake Tekapo is $40.7/MWh [41], and therefore FPV systems may already be economic feasible in certain contexts in Aotearoa–New Zealand.

Conclusions and way forward

The analyses of specific cases in the Aotearoa–New Zealand context

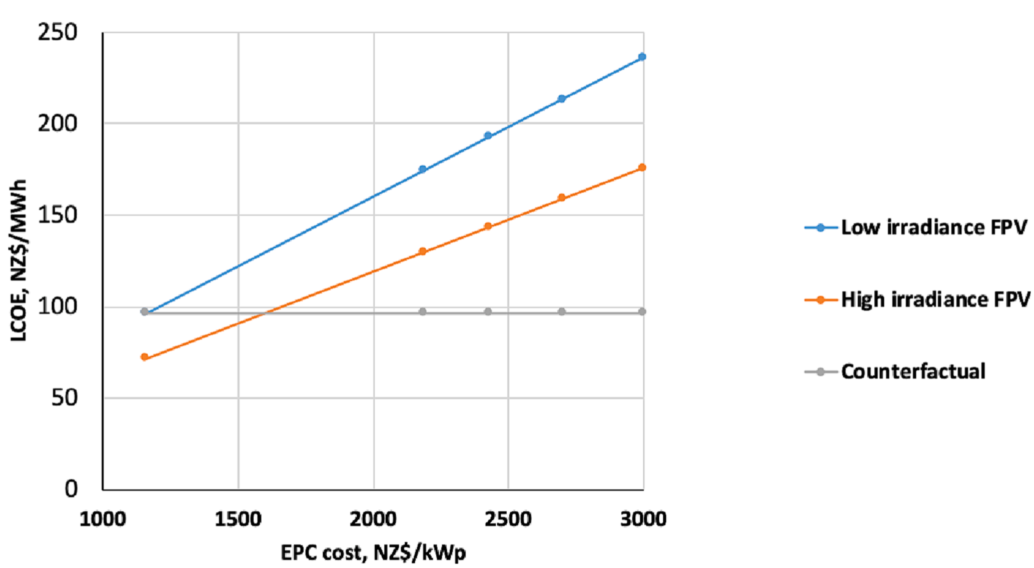

Fig. 4. Sensitivity of the LCOE to EPC cost considering temperature effects as per primary manufacturing costs of pontoons to date.

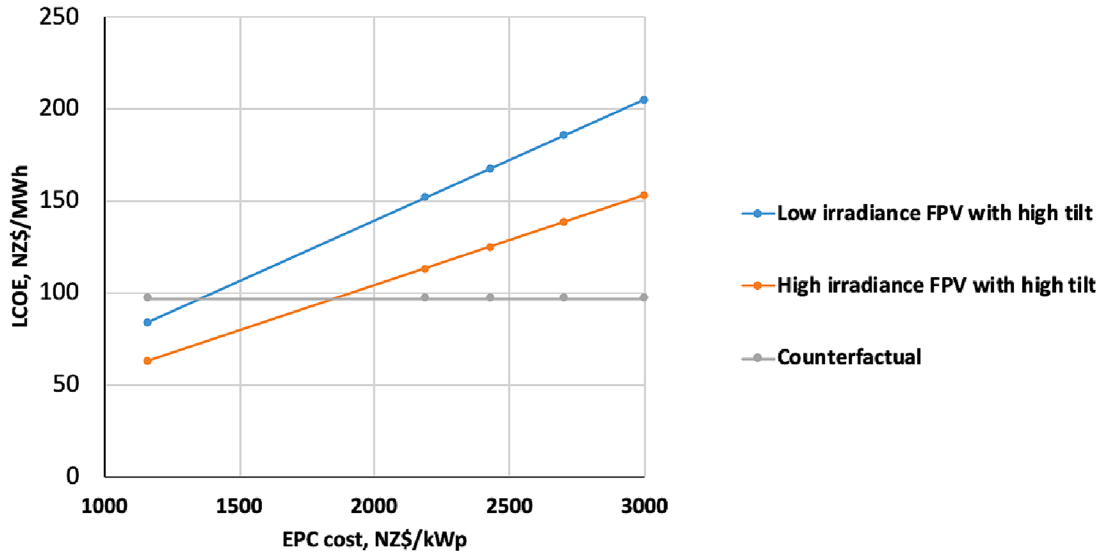

Fig. 5. Sensitivity of the LCOE to EPC cost with higher tilt modules.

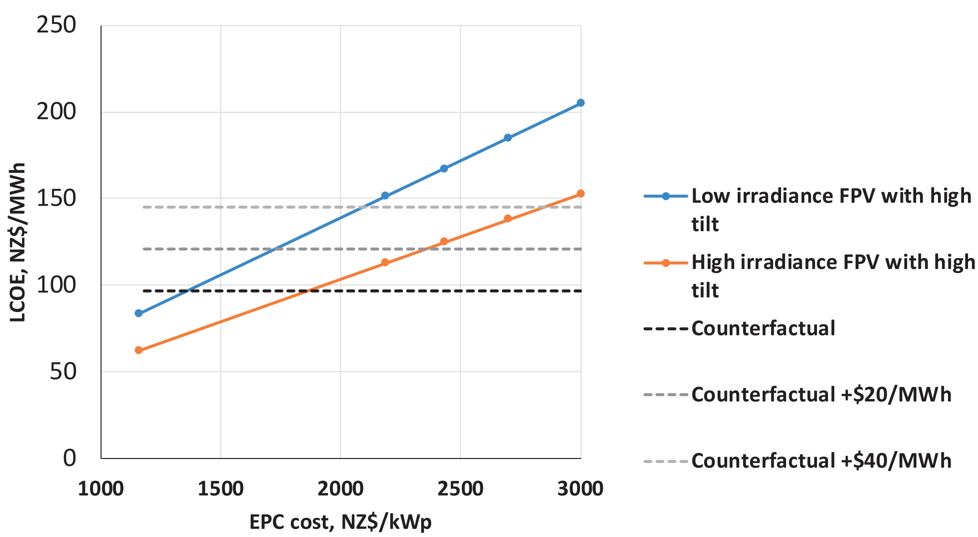

Fig. 6. Sensitivity of the LCOE of FPV with higher tilt modules when compared to counterfactual behind the meter pricing scenarios.

indicates the costs and technical performance required to make FPV systems economically feasible. Using the models of Solargis with industry standard technical specification for FPV systems, and considering the normal uncertainties associated with (potential) FPV performance evaluations, as well as the influence of water temperature for the site-specific contexts, the overall FPV output is estimated to be between 1,115 and 1,497 kWh/kWp installed at feasible sights in Aotearoa–New Zealand at typical FPV tilt values. With current EPC costs, the levelized cost of energy (LCOE) metric is determined to be between NZ$176.0 and NZ$236.3 per MWh, with total electricity generation over 25 years between 262.7 and 352.6 GWh – from a 10 MW installation, which included the influence of water temperature (see Table 2). In order to reach the required counterfactual LCOE value of NZ$96.6/MWh, the EPC costs will have to be reduced by a factor of 2 to around NZ$1500/kWp, which is higher than required projections [16], and similar to the current cost of ground-mounted systems with the state of the art bi-facial PV modules and tracking [42].

If future pontoon designs can accommodate PV modules at optimal tilt angles, without increasing the construction and maintenance costs significantly, the financial feasibility of FPV systems can be improved by around 13%, although such systems will still be in the order of 60% more expensive than adding marginal generating systems to the grid. A sensitivity analysis shows that FPV may provide cost competitive electricity in behind the meter scenarios when variable charges are considered. However, further analysis is needed to identify customers in the vicinity of FPV locations. In addition, to support the uptake of FPV

Table 2
LCOE for the different scenarios.

Scenario	Maraetai (Low solar resource)*		Tekapo (High solar resource)*	
	kWh/kWp	NZ $/MWh	kWh/kWp	NZ $/MWh
Ground-based PV system	1224	215.30	1645	160.20
FPV	1062	248.10	1425	184.90
FPV and water influence	1115	236.30	1497	176.00
FPV with optimal tilt and water influence	1287	204.70	1726	152.60

*Low solar resource includes a −4.8% uncertainty, and High solar resource includes a +4.8% uncertainty.

systems in Aotearoa–New Zealand, and elsewhere, further research is needed into:

- Design options and construction methods. As stated above, an advantage of FPV systems is the increased panel density for a given area due to lower tilt angles. However, the implication is an around 13% lower energy output (for the specific New Zealand cases), which means a greater area will be required to increase the energy output. A critical issue is then how the pontoon component of FPV systems are designed for local manufacturing and other cost reduction opportunities associated with logistics, building on current documented experiences [43].
- Site-specific measurements. In-situ monitored data is required on the lakes and dams of Aotearoa–New Zealand, especially the solar resource, low-level wind, and water temperatures; so that these influences on FPV output performances can be better evaluated, as well as the potential evaporation effects from installed FPV systems, which is documented in literature [12].
- New pontoon technology for high latitude regions. Specific designs of pontoons that can support higher module tilt angles than are commonly used on FPV installations around the world needs to be investigated.

Funding

This work was supported by the University Research Fund of Victoria University of Wellington under Grant number 222568.

CRediT authorship contribution statement

Alan C. Brent: Conceptualization, Methodology, Formal analysis, Validation, Writing – review & editing. **Andrew Crossland:** Methodology, Formal analysis, Validation, Writing – review & editing. **Daniel Ranusa:** Data curation, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the industry participants that provided valuable information.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103284.

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