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Techno-economic analysis of a 10 kWp utility interactive photovoltaic system at Maungaraki school, Wellington, New Zealand

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ABSTRACT

This paper presents a performance analysis and economic viability of a 10 kWp grid-connected solar photovoltaic (PV) system installed at Maungaraki school, Wellington, New Zealand under the "Dynamis Project". The system consists of 40 panels and two units of 5 kW power converters with a communication capability while the distribution grid serves as a virtual storage. The excess power generated at low load condition during holidays and weekends is exported to the grid. With the system in operation since 2014, performance parameters based on International Energy Agency Photovoltaic Power System Programme (IEA PVPS), Clean Energy Council industry guide and IEC 61724 standard are evaluated. The final yield ranged from 1.1 to 4.9 h/d. The performance ratio (PR) varied between 76 and 79%, giving an annual PR of 78%. In addition, from the economic evaluation of this system at 4%, 6% and 8% discount rates, the levelized cost of energy are 12.1, 14.1 and 16.2 c/kWh respectively, with a simple payback period of 6.4 years. Overall, the total amount of power consumed annually from the grid reduced significantly by 32%. In monetary terms, the school's expenditure on power bills reduced effectively by 45% and was able save about NZD $4700 in 2014.

1. Introduction

The recent energy transition as a result of the growing presence of renewable energy resources (such as wind power, solar energy and hydropower) in the conventional power system is pivotal in dealing with climate change, enhancing power network resilience and provision of new economic opportunities [1–3,49,50]. One of the most common renewable energy resources is the photovoltaic (PV) system such as the rooftop residential and utility scale installations [4]. However, hydroelectric generation supplies the bulk of New Zealand's electricity demand, geothermal contributes about 17.2% while wind generation is about 5.4% of the country's power generation [5]. In a recent quarterly electricity generation report, solar power contributed 0.1% (as shown in Fig. 1) of the country's net electricity generation of about 42927.54 GWh at the end of 2015 [5].

The contribution of solar photovoltaic (PV) systems is quite insignificant when compared to the deployment of other renewables in New Zealand. However, in recent times, there is a widespread deployment of rooftop grid-connected PV systems in residential apartments and schools as reported in this article. The proliferation of such systems on the electricity grid highlights the need to understand its operation through monitoring and thorough performance analysis [6]. In addition, utility interactive PV systems are essentially monitored to evaluate the final energy yield, detect possible design defects and avoid economic losses as a result of operational issues [6]. Another reason to carry out such analysis is to assess PV credibility, viability and ultimately to increase their penetration within the existing electric power network [7].

The IEA PVPS Task 2 has been able to analyse and publish 170 grid-connected PV systems installed in various countries of the world [8]. In addition, over the previous years, various authors from different countries have published results of the performance analysis of their respective grid-connected PV units. Pietruszko et al. [9] evaluated the performance of a 1 kWp a-Si PV system located at Warsaw, Poland. The performance ratio ranged from 0.6 to 0.8, annual system yield was 830 kWh and the efficiency of the PV system was in the range of 4–5%. Mondol et al. [10] presented the outcome of the performance analysis of a 13 kWp m-Si PV system installed in Northern Ireland. The evaluated annual final yield ranged from 1.61 to 1.76 h/d, with a PR which ranged from 0.6

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Nomenclature

η_{sys}	system efficiency
λ	power temperature coefficient(−0.45%/°C)
$\mu a - Si$	micromorph silicon
$a - Si$	amorphous silicon
A_{array}	area of the array (m^2)
AC	alternating current (A)
DC	direct current (A)
G_I	in-plane solar irradiation (kWh/m^2)
$G_{I,ref}$	reference irradiance (kW/m^2)
h/d	hour/day
L_c	array capture losses
L_s	system losses
L_{SP}	capacity factor
$LCOE$	levelized cost of energy
$m - Si$	mono crystalline silicon
NPV	net present value
$p - Si$	poly crystalline silicon
P_O	rated DC output power of the array under standard test conditions (Wp)
PR	performance ratio
$semi - Si$	semi crystalline silicon
T_A	ambient temperature (°C)
T_C	cell temperature (°C)
T_R	temperature rise for parallel-to-roof installation (°C)
T_{STC}	cell temperature at standard test conditions (°C)
$TLCC$	total life cycle cost
Y_A	array yield (kWh/kWp)
Y_f	final yield (kWh/kWp)
Y_r	reference yield (kWh/kWp)

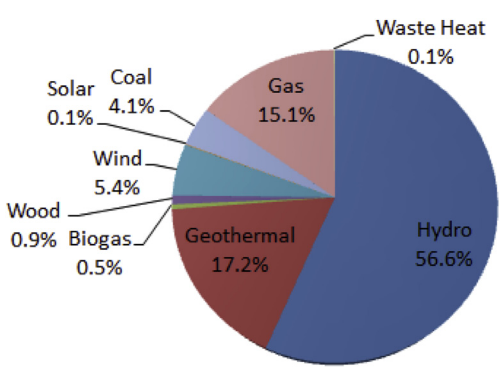

Fig. 1. Electricity generation from various energy sources in New Zealand [5].

to 0.62 and annual average system efficiency of 6.4%. Also, Chokmaviroj et al. [11] evaluated the performance of a 500 kWp grid-connected PV plant at Mae Hong Son province, Thailand. The plant was divided into two, 250 kWp, from a double glazed semi-Si PV modules. The plant generated about 383274 kWh and the efficiency of the PV array ranged from 9 to 12%. The final yield ranged from 2.91 to 3.98 h/d and the PR ranged from 0.7 to 0.9.

Another performance study is that of Kymakis et al. [12]. The study evaluated a p-Si 171.36 kWp utility interactive PV park on the island of Crete, which was as a result of the favourable climatic condition and the recent incentivization of PV system installations in Greece. The yearlong evaluated PR was 0.67 and the final yield ranged from 1.96 to 5.07 h/d. Cherfa et al. [13] carried out an analysis of a mini-grid connected m-Si 9.54 kWp PV system which was a pilot project with the primary aim of acquiring experience in the design, monitoring and maintenance of such innovative technology in Algeria. The system performance was quantified over the monitored period which showed an annual 10981 kWh of energy injected into the grid. The average daily output energy was 30 kWh and PR ranged from 0.62 to 0.77. Ayompe et al. [14] presented results obtained from monitoring a m-Si 1.72 kWp rooftop grid-connected PV system in Ireland. Within the frame of the study, the monthly average daily capacity factor ranged from 5 to 15.5%, with an annual average of 10.1%. The PR and final energy were 0.82 and 2.4 h/d respectively. Another relevant study is that of Okello et al. [15] in South Africa. They presented the analysis of p-Si 3.2 kWp grid-connected PV system with a PR of 0.84 and final energy yield of 4.9 h/d.

Performance analysis of different utility interactive PV sizes have been conducted across various locations in India. For instance, Sharma and Chandel [16] investigated the performance of a p-Si 190 kWp PV plant connected to the grid in Punjab, northern India. The final yield, reference yield and PR ranged from 1.45 to 2.84 h/d, 2.29–3.53 h/d and 55–83% respectively. The annual average PR, capacity factor and system efficiency were found to be 74%, 9.27% and 8.3% respectively. Also, Padmavathi et al. [17] presented an analysis of a m-Si 3 MWp grid-connected PV plant in Karnataka, south western region of India. The annual average energy generated was 1372 kWh per kW of the installed capacity and the PR was 0.7. The annual average reference yield and final yield were 5.36 h/d and 3.73 h/d respectively. In addition, Shiva Kumar and Sudhakar [18] analysed the performance of a p-Si 10 MWp PV plant connected to the grid at Ramagundam, southern India. The plant is one of the largest solar power plants with a seasonal tilt. Results revealed that the capacity utilization factor was 17.68% with an annual energy generation of 15 798.192 MWh. The final yield ranged from single-phase1.96–5.07 h/d, and annual PR was 0.86. Sundaram et al. [19] evaluated the performance analysis of a thin film a-Si 5 MWp grid-connected PV plant at Sivagangai district in Tamilnadu, south India. The annual actual generation was 8495.29 MWh with a system efficiency of 5.08%. The final yield, PR, average energy and exergy efficiency were found to be 4.81, 0.89, 6.08% and 3.54% respectively.

Edalati et al. [20] presented a comparative performance analysis of m-Si (5.52 kWp) and p-Si (5.52 kWp) for utility interactive PV systems in dry climates. The annual average capacity factor for m-Si and p-Si were found to be 23.20% and 23.81% respectively. The annual final yield and PR for p-Si were 5.38 h/d and 0.83 respectively. Moreover, the annual final yield and PR for m-Si were 5.24 h/d and 0.81 respectively. Sidi et al. [21] evaluated the performance analysis of the first utility-scale 15 MWp grid-connected PV plant in Mauritania, which has a high annual insolation between 1900 and 2200 kWh/m^2/year. The PV plant from a-Si/μ a-Si was connected to the 33 kV electricity grid through inverters and nine transformers. Performances of two arrays from two different technologies, $\mu a - Si$ and a-Si were presented. The daily average array yield, PR, and capacity factor for $\mu a - Si$ were 4.38 h/d, 0.68 and 17.75% respectively. Moreover, the daily average array yield, PR, and capacity factor for a-Si were 4.79 h/d, 0.75 and 19.54% respectively.

These performance metrics allow cross-comparison between different PV systems in terms of design, technology and diverse

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