Simulating the Expansion of Community-based Photovoltaic Electricity Generation for Energy Autonomy

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ABSTRACT

This paper reports a case study that involved studying and simulating the potential for photovoltaic (PV) electricity generation at Hojing Elementary School by using the RETScreen model. The electricity generation simulated by the existing 3.67-kW PV power system for 2011 was 5,428 kWh, which was very similar to the actual electricity generation for that same year (5,427.7 kWh). However, inaccuracies in the simulations over 8 months were greater than 10%. Based on the total rooftop area available for installing PV panels, a capacity of 355.12 kW and a total electricity yield of 174% of the school's electricity demand can be achieved. The validation of the RETScreen model in this study indicated that the model is able to accurately simulate the yearly technical potential of proposed PV projects. However, the reliability of the model to analyze the potential monthly electricity generation of the proposed project needs to be enhanced.

Keywords: photovoltaic electricity generation, simulation of potential, RETScreen, energy autonomy

能源自主導向下社區擴大太陽光發電之模擬

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摘　　要

本研究探討利用 RETScreen 模型模擬後勁國小太陽光電潛力。模擬現有 3.67 千瓦太陽光電系統 2011 年發電量為 5,428 度，與實際發電量 5,427.7 度極為接近，但有 8 個月模擬值的不準確度高於 10%。依據校舍屋頂可安裝光電板的屋頂面積計算，共可安裝 355.12 千瓦的太陽光電板，可供應學校總用電量的 174%。本研究的驗證顯示 RETScreen 模型可以準確模擬太陽光電每年的技術潛力，但分析每月發電量的可靠度仍有待提升。

關鍵詞：太陽光電，潛力模擬，RETScreen，能源自主

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I. INTRODUCTION

The application of photovoltaic (PV) power generation has rapidly increased in recent years. However, although the global potential of PV power generation is considerable [1,2], the amount of electricity actually produced using this technology remains limited compared with that produced using traditional fossil-fuel-burning power plants. This slow penetration of PV power into the energy market has delayed the transition toward a low-carbon energy system. One notable difficulty that impedes the widespread application of PV power systems is the fact that distributed power generation through PV systems heavily relies on the owners of nonutility buildings, who generally do not recognize the potential benefits of installing PV technology on their rooftops. Through a case study of Hojing Elementary School, this study examined whether the RETScreen software is suitable for evaluating the technical and economic potential of installing or expanding PV power systems for potential investors worldwide. Hojing Elementary School was selected because it operates a 3.57-kW PV power system, the performance of which was used to verify simulation results.

Hojing Elementary School is located in Kaohsiung City in southwestern Taiwan (Fig. 1). The school comprises five 3- to 5-story buildings, and has a total rooftop area of 6,296.9 m^2. A total of 971 students and 75 faculty members attended or worked at the school in 2011.

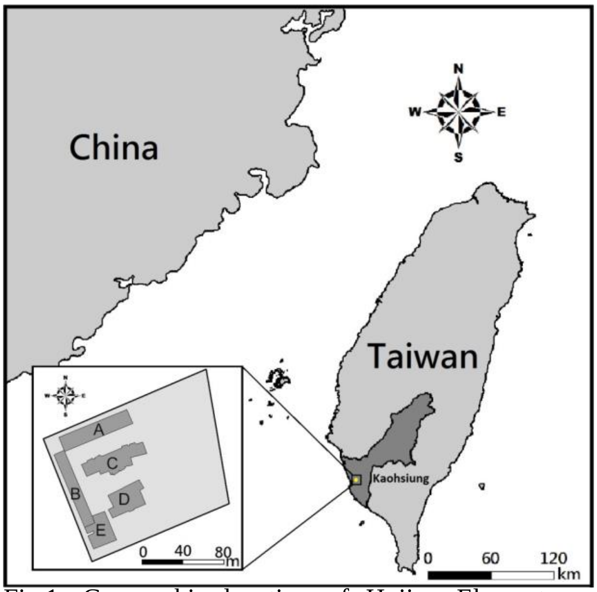

Fig.1. Geographic location of Hojing Elementary School and the distribution of its five main buildings.

Ⅱ. LITERATURE REVIEW

Numerous studies have analyzed the integration of renewable energy into various energy systems. RETScreen has been one of the most widely used tools worldwide for evaluating the technical and economic potential of renewable projects [3]. It was specifically developed to evaluate the energy production, life-cycle costs, and greenhouse gas (GHG) emission reductions of various types of energy efficient and renewable energy technologies, and can be used to evaluate industrial, commercial, institutional, community, residential, and utility applications.

The RETScreen model has been applied in several studies to evaluate the project feasibility of PV systems [4,5,6,7]. Bakos et al. evaluated a grid-connected building-integrated PV (BIPV) system installed in northern Greece [8]. Technical and economic factors were examined using RETScreen, and numerous economic and financial feasibility indices were calculated to assess the gross return on investment in different financing scenarios. The authors concluded that BIPV systems were feasible, and suggested that such systems had the potential to play a key role in the energy market. Harder and Gibson examined the potential of a 10-MW PV power plant in Abu Dhabi, using RETScreen to predict energy production, financial feasibility, and GHG emission reductions. The results indicated that the high initial costs and low expected price for electricity generated were the reasons that PV systems have not been implemented in Abu Dhabi. A feed-in tariff rate of US$0.16/kWh was recommended to make large-scale PV systems profitable [9].

Mondal and Islam assessed the financial viability of solar PV systems as an electricity-generating source for Bangladesh, using a proposed 1-MW grid-connected solar PV system. A RETScreen simulation model was constructed for 14 locations in Bangladesh. For each location, the site conditions (i.e., site latitude, monthly solar radiation on horizontal surfaces, and monthly mean temperature) and specifications and parameters of the solar PV system were input in the RETScreen simulation software. Then, an economic feasibility analysis was conducted and the energy produced by the system was calculated; the authors also determined by how much GHG emissions could be reduced if Bangladesh used the PV system for electricity generation instead of fossil fuel plants. Economic and financial indicators, such as the internal rate of return (IRR), net present value (NPV), cost–benefit ratio, energy production cost, and simple payback, were calculated [10]. In comparison to the study by Mondal and Islam (which simulated a PV system spread over several locations), the present study estimated the overall power generation potential of a single location. PV panels were installed on all available and suitable rooftop areas of the buildings of Hojing Elementary School based on a data analysis of the existing 3.67-kW grid-connected solar PV system. The main advantage of the current study lies in the possibility of validating the simulation result with actual measured data.

In addition to PV power generation, RETScreen models have been used to perform economic feasibility studies of other renewable energy sources. For example, Rodríguez used RETScreen to analyze the potential of wind resources to produce hydrogen in Argentina, by determining what threshold price of eolic MWh (null NPV) makes eolic farming profitable [11]. Himri and Rehman et al. have also used RETScreen modeling to perform economic feasibility studies of wind farms in Algeria and Saudi Arabia [12,13].

Although RETScreen has been widely applied in these studies to evaluate the feasibility of renewable energy projects, the accuracy of this model has not been validated with actual electricity generation data. In response, this study aimed to validate the RETScreen model by analyzing the model's performance in evaluating the technical and financial potential of a PV power project.

Ⅲ. METHODOLOGY

3.1 Overview of adopted methods

Fig. 2 shows an overview of the procedures performed in this study. These procedures are also described in the following five steps:

(1) The performance and output of the 3.67-kW PV power system were simulated by inputting geographical and technical data into the RETScreen software.
(2) The simulation model was validated by comparing the simulated electricity production with actual electricity production.

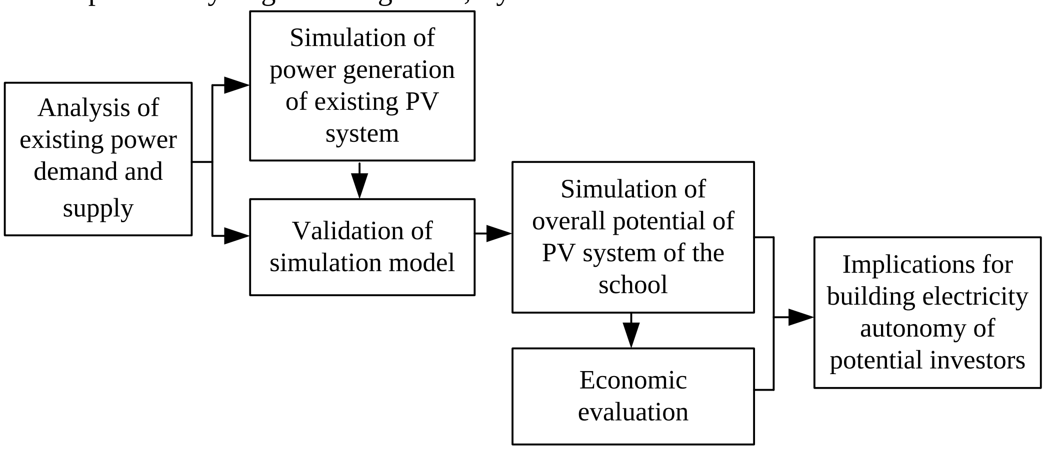

Fig.2. Overview of study procedures. The existing power demand and supply were investigated and used as a reference for further study of energy autonomy.

(3) The overall power generation potential was simulated by installing PV panels on all available and suitable rooftop areas of the school buildings.

(4) An economic evaluation was performed, which comprised simulating the IRR and equity payback of investments, using the RETScreen model.

3.2 Simulation tool

The RETScreen model provides a methodology for comparing conventional and clean energy technologies. Fundamental to the model is a comparison between a “base case” (typically the conventional technology or measure) and a “proposed case” (the clean energy technology). A RETScreen analyst can focus on conducting a prefeasibility study by combining the tool’s minimal data input requirements and built-in weather and product databases. This permits the screening of multiple potential projects, such that the most promising ones can be identified and implemented.

The five-step standard project analysis of the RETScreen model includes an energy model, cost analysis, GHG analysis, financial summary, and sensitivity and risk analysis.

STEP 1 - Energy Model:

In this worksheet, parameters describing the location of the energy project, type of system used in the base case, technology for the proposed case, loads, and renewable energy resource are specified. Subsequently, RETScreen calculates the annual energy production or energy savings. A resource worksheet, “Equipment Data” worksheet, or both accompanies the Energy Model worksheet as subworksheet(s).

STEP 2 - Cost Analysis:

In this worksheet, the initial, annual, and periodic costs for the proposed case system, as well as credits for any base case costs that are avoided in the proposed case, are provided. Next, either a prefeasibility or feasibility study is performed. Less detailed and less accurate information is required for a “prefeasibility analysis,” whereas more detailed and more accurate information is required for a “feasibility analysis.”

STEP 3 - GHG Analysis (optional):

This optional worksheet helps to determine the annual reduction of GHG emissions that stem from using the proposed technology in place of the base case technology. The analyst chooses between performing a simplified, standard, or custom analysis, and can also indicate if the project should be evaluated as a potential Clean Development Mechanism (CDM) project. RETScreen automatically assesses whether or not the project can be considered a small-scale CDM project, which adopts simplified baseline methods and other rules and procedures for small-scale CDM projects.

STEP 4 - Financial Summary:

In this worksheet, the analyst specifies the financial parameters of the project, including the energy costs that are avoided, production credits, GHG emission reduction credits, incentives, inflation, discount rate, debt, and taxes. Then, RETScreen calculates a variety of financial indicators (e.g., net present value) to evaluate the viability of the project. A cumulative cash flow graph is also included in the financial summary worksheet.

STEP 5 - Sensitivity & Risk Analysis (optional):

This optional worksheet helps to determine how uncertainty in the estimates of various key parameters may affect the financial viability of the project. The analyst can perform a sensitivity analysis, a risk analysis, or both [14].

The RETScreen model uses both meteorological and product performance data as input for various technology models, which are used to determine the amount of energy that a project can deliver; additional data regarding costs and other financial parameters are required to determine various financial aspects of the project. When the location of a community is entered, the average local temperature, humidity, and global solar radiation during the previous 30 years are derived from the meteorological database built into RETScreen. This database contains ground-based meteorological data and satellite-derived meteorological datasets from the National Aeronautics and Space Administration (NASA), both of which provide weather and climate data for the entire surface of the earth [14]. Using the meteorological data of NASA instead of Taiwan's in this study was intended, in order to validate the accuracy of the RETScreen database and simulation. Because of the suitability of the RETScreen model for feasibility studies of renewable energy projects, the present study adopted this tool to simulate the expansion of community-based PV electricity generation for energy autonomy.

Ⅳ. EXISTING ELECTRICITY DEMAND AND SUPPLY

In 2011, Hojing Elementary School's power bill was US$30,011 and its total electricity consumption was 308.4 MWh. This was slightly lower than that its 2010 consumption (323.8 MWh). Peak electricity consumption occurred mainly in May, June, September, and October, corresponding with the use of air conditioning during those months. By contrast, less electricity was consumed during winter and summer vacation in February, July, and August (Fig. 3). The weather statistics indicated that the average temperatures in Kaohsiung from May to October of 2011 all exceeded 26 ℃, which is highly consistent with the peak power consumption from air conditioning that occurred during the same period.

The electricity demand of the school is mainly supplied by national grid. As indicated in Fig. 4, a grid-connected 3.67-kWp PV power system fully funded by the Bureau of Energy of the Republic of China was installed on the rooftop of Building A (Fig. 1) in 2009.

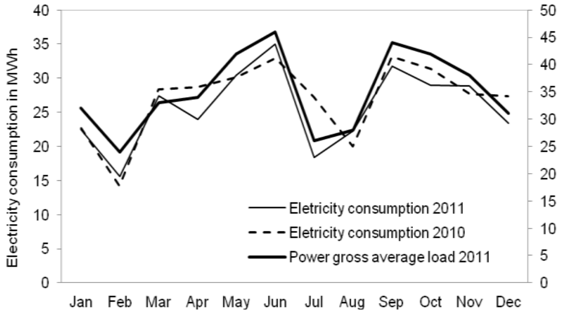

Fig.3. Power load and electricity consumption of Hojing Elementary School.

Fig.4. Operational PV power system on the rooftop of Building A of Hojing Elementary School.

V. SIMULATION OF ELECTRICITY GENERATION

Power generation by the existing PV power system was simulated using RETScreen to set the grid type to central grid and internal load (Table I). The electricity generated using this mode is used internally by the school. Notably, the grid has a deficit when the PV-generated electricity is insufficient for the demand; however, any available surplus electricity from the PV power system after energy is consumed by the school is exported to the grid. The gross average power load for every month must be provided in the data input item "Load and Network". The simulation was performed after providing other required specifications for the simulation setup and technical data, and the simulated electricity generation for 2011 was 5,428 kWh (Table II).

Table I. Specifications for the simulation setup and technical data of the 3.67-kW PV power system at Hojing Elementary School

Category	Item	Input
Project Information	Project type Technology Grid type	Power Photovoltaic Central-grid & internal load
Site reference Condition	Country - region Climate data location	Taiwan Kaohsiung
Resource assessment	Solar tracking mode Slope Azimuth	Fixed 23° -23°
PV	Type Area Power capacity Manufacturer Model Efficiency Miscellaneous loss	mono-Si 28 m^2 3.67kW Apin Solar mono-Si-SP180 13.9% 3%
Inverter	Efficiency Capacity Miscellaneous loss	95% 4kW 3%
Summary	Capacity factor Electricity exported to grid	16.9% 5,428 kWh/year

Table II. Simulated electricity generation by the 3.67-kW and 355.12-kW PV power systems at Hojing Elementary School (2011)

Month	Daily solar radiation		Electricity exported to grid	
	horizontal	tilted	3.67 kW	355.12 kW
	$kWh/m^2/d$	$kWh/m^2/d$	kWh	MWh
Jan	3.61	4.36	416	39.9
Feb	3.88	4.34	375	36.5
Mar	4.69	4.92	465	45.9
Apr	5.28	8.18	469	47.0
May	5.58	5.20	485	49.2
Jun	5.78	5.25	471	48.1
Jul	6.04	5.53	510	51.9
Aug	5.44	5.22	482	48.5
Sep	4.99	5.10	455	45.2
Oct	4.68	5.20	479	46.7
Nov	3.85	4.54	410	39.5
Dec	3.51	4.35	411	39.3
Annual	4.78	4.94	5,428	537.7

The simulated electricity generation for 2011 (5,428 kWh) was very similar to the actual electricity generation (5,427.7 kWh) of that same year, although inaccuracies in the simulations over 8 months were greater than 10% (Table III and Fig. 5). These differences may be attributed to the fact that RETScreen adopted the average solar irradiation over the previous 30 years from NASA weather data, because those irradiation values differed from the actual solar irradiation in 2011.

Table III. Accuracy of simulated electricity generation by the 3.67-kW PV power system at Hojing Elementary School (2011)

Month	Simulated electricity generation	Actual electricity generation	Inaccuracy[a] (%)
Jan	416	396.8	4.8
Feb	375	425.9	-12.0
Mar	465	476.0	-2.3
Apr	469	361.5	29.7
May	485	570.3	-15.0
Jun	471	479.5	-1.8
Jul	510	645.8	-21.0
Aug	482	430.5	12.0
Sep	455	495.3	-8.1
Oct	479	434.8	10.2
Nov	410	352.8	16.2
Dec	411	358.5	14.6
Total	5428	5427.7	0.0

[a] Inaccuracy = [(Simulated electricity generation)−(Actual electricity generation)]/(Actual electricity generation) × 100%

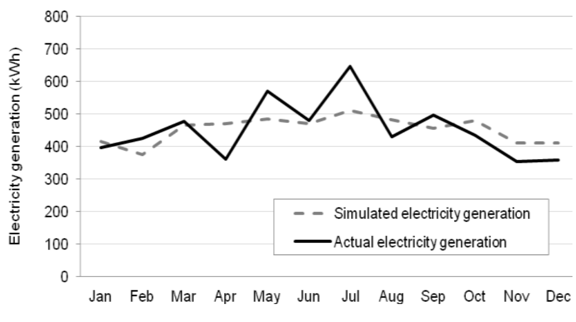

Fig.5. Simulated and actual electricity generation by the existing 3.67-kWp PV power system (2011).

The actual electricity production of the operating 3.67-kWp PV power system in 2011 (5,427.7 kWh) only provided 1.8% of the school's total electricity consumption (308,440 kWh) that year. Because the five main buildings have a total rooftop area of 6,296.9 m^2 and the ratio of the roof area suitable for PV panels to the total roof area is assumed to be 0.4 [15], a rooftop area of approximately 2,519 m^2 was determined to be available for PV panel installation. A usage factor of 0.4 accounted for both architectural and solar suitability. Architectural suitability includes corrections for the limitations caused by construction, historical considerations, shading effects, and the available surfaces being used for other purposes. Solar suitability accounts for the relative amount of irradiation on the surfaces, depending on their orientation, inclination, and location, as well as the potential performance of the PV power system installed on the building. According to the RETScreen estimation, a total capacity of 355.12 kW with a total electricity yield of 537.7 MWh could be achieved for 2011 (Table II and Fig. 6). This indicates that Hojing Elementary School has the potential to supply 174% of its electricity demand. Moreover, the parallel occurrence of the peak load and power generation from PV power systems can be clearly observed, providing excellent conditions for stabilizing the power supply of the grid in the summer.

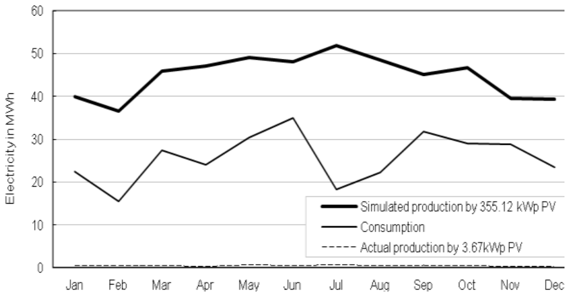

Fig.6. Comparison of PV power generation with electricity demand at Hojing Elementary School (2011).

Ⅵ. ECONOMIC EVALUATION

An economic evaluation of PV power systems was also performed in this study. Specifically, the IRR and equity payback of investments in PV power systems were simulated using RETScreen and the following parameter assumptions:

- Installation capacity of 355.12 kW;
- Technical lifetime of 25 years;
- Initial cost of US$2,852/kW [16];
- Yearly operating and maintenance costs of 0.7% of the initial cost [17];
- Inflation rate of 1.8% [18];
- Feed-in tariff of US$0.27/kWh [19].

Investors may install a PV power system that includes a parallel feed with either an internal or external connection to the grid, according to the current code in Taiwan. An internal connection refers to a grid connection that has its point of parallel connection inside the school. Hojing Elementary School uses a higher-than-standard power supply. Therefore, if a parallel feed with an internal connection is used, a booster to transform the voltage must be installed at an additional cost of US$0.5/kW [16]. Notably, a grid with an internal connection can only be fed with residual electricity that is output according to the operator's use. By contrast, an external connection refers to a grid connection that has its point of parallel connection outside the school. The entire electricity output of a PV power system can be fed into a grid that has an external connection.

A comparison of the financial investments in PV power systems (Table IV) indicated that a system with an external connection would yield substantially more revenue (US$147,664) than a system with an internal connection (US$67,182). This is because externally connected systems can export their entire electricity output with a feed-in tariff (US$0.27/kWh) that is considerably higher than the price of electricity (US$0.096/kWh), which leads to a difference between the sum of annual fuel cost savings and electricity export income (US$147,664 for systems with external connections and US$96,892 for systems with internal connections) and thus to a difference in the IRR. Investments in PV power systems with internal and external grid connections were calculated to potentially yield IRRs of 12.4% and 19.4%, respectively, with payback periods of 8.1 and 5.4 years, respectively. Obviously, an investment in a PV power system with an external connection is more lucrative than an investment in a system with an internal connection. Investing in installing a PV power system with both internal and external connections to the grid also seems attractive considering the 25-year technical lifetime and short payback period. Indeed, expanding the installation capacity from the existing 3.57 kW to 355.12 kW would reduce the initial cost per kilowatt by 20% [20].

VII. CONCLUSIONS AND IMPLICATIONS

The present study evaluated the technical and economic potential of expanding the PV project at Hojing Elementary School, and elicited the following novel findings:

1. The simulated electricity generation (5,428 kWh) and actual electricity generation (5,427.7 kWh) of 2011 were very similar. However, inaccuracies in the simulations over 8 months were greater than 10%. These differences may be attributed to the fact that RETScreen adopted the average solar irradiation over the previous 30 years from NASA weather data, because those irradiation values differed from the actual solar irradiation in 2011.
2. The actual electricity production by the operational 3.67-kWp PV power system (5,427.7 kWh) provided only 1.8% of the school’s total electricity consumption (308,440 kWh) in 2011. Based on the total rooftop area available for installing PV panels, a capacity of 355.12 kW and a total electricity yield of 537.7 MWh, which would account for 174% of the school’s electricity demand, can be achieved.
3. Considering the current feed-in tariff and regulations for grid connections in Taiwan, internal and external grid connections would yield IRRs of 12.4% and 19.4% and equity paybacks of 8.1 and 5.4 years, respectively. Although both options provide lucrative incentives, investing in an external connection appears more financially favorable.
4. Overall, the results of this study indicate that RETScreen is able to accurately simulate the yearly technical potential of proposed PV projects. However, the reliability of the model to analyze the potential monthly electricity generation of the proposed project needs to be enhanced.

Numerous PV power projects worldwide could serve as pilot projects for testing the performance and viability of PV technologies in local climatic and institutional contexts. Achieving complete energy autonomy requires a viable tool for facilitating feasibility evaluation of expanding PV power systems. The validation of RETScreen in this study may foster understanding of the model's performance and limitations in evaluating the technical and financial potential of a PV power project. This would enable potential investors, such as residential communities, schools, and business companies, to evaluate the feasibility of investment in clean energy projects intended to either reduce CO_2 emissions associated with electricity consumption or increase energy autonomy.

Table IV. Financial comparison of investments in internally and externally connected PV power systems

	Internal	External
Initial costs (US$)	805,547.9	805,369.1
Exported electricity (US$)	67,182	147,664
Annual savings of fuel cost (US$)	29,710	0
Electricity export income (US$)	67,182	147,664
Sum of Annual savings of fuel cost & electricity export income (US$)	96,892	147,664
IRR (%)	12.4	19.4
Equity payback (year)	8.1	5.4

VIII. FUTURE RESEARCH DIRECTIONS

While this study provided an example to model and analyze solar PV configurations, there were some limitations that may be addressed in future studies. First, RETScreen does not account for solar PV array degradation that would affect the payback years of the investment. The model would need to include this factor to enhance the accuracy of its technical and economic evaluations. Second, data for different years should be collected to compare and evaluate the effectiveness of the proposed simulation model over time. The instant monitor system of power output of the existing 3.67-kWp PV system analyzed in this study has unfortunately failed over the last few years, rendering power output data from recent years unavailable. In addition, RETScreen uses average meteorological data from the preceding 30 years to estimate the local power generation of PV modules. However, it can only estimate the power generation in the year of evaluation, meaning that retrospective estimation of power generation is not possible. A comparative analysis would therefore require database and simulation validation to be conducted every year. Finally, because the accuracies of monthly simulations are affected by the long-term NASA weather database, a transient simulation and experimental validation of the actual usage of electricity with regard to buildings' energy consumption needs further study. Such an investigation could provide insight into the transient and dynamic relationship of electricity demand and supply in different seasons.

In conclusion, RETScreen was validated in this study, and was confirmed to be a suitable tool for overcoming barriers to clean energy technology implementation at the preliminary feasibility stage. The aforementioned future directions would further improve the model's performance and facilitate the use of this tool for renewable energy application.

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