2-1-2024

Machine learning-enhanced all-photovoltaic blended systems for energy-efficient sustainable buildings

Mohammad Nur-E-Alam
Edith Cowan University

Kazi Z. Mostofa

Boon K. Yap

Mohammad K. Basher
Edith Cowan University

Mohammad A. Islam

See next page for additional authors

10.1016/j.seta.2024.103636
Nur-E-Alam, M., Mostafa, K. Z., Yap, B. K., Basher, M. K., Islam, M. A., Vasiliev, M., . . . Kiong, T. S. (2024). Machine learning-enhanced all-photovoltaic blended systems for energy-efficient sustainable buildings. Sustainable Energy Technologies and Assessments, 62, article 103636. https://doi.org/10.1016/j.seta.2024.103636

Authors

Mohammad Nur-E-Alam, Kazi Z. Mostofa, Boon K. Yap, Mohammad K. Basher, Mohammad A. Islam, Mikhail Vasiliev, Manzoore E. M. Soudagar, Narottam Das, and Tiong S. Kiong

Sustainable Energy Technologies and Assessments 62 (2024) 103636

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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

Machine learning-enhanced all-photovoltaic blended systems for energy-efficient sustainable buildings

Mohammad Nur-E-Alam [a,b,c,*], Kazi Zehad Mostofa [d], Boon Kar Yap [a,e], Mohammad Khairul Basher [b], Mohammad Aminul Islam [d], Mikhail Vasiliev [f], Manzoore Elahi M. Soudagar [g], Narottam Das [c,h], Tiong Sieh Kiong [a,e]

[a] *Institute of Sustainable Energy, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia*
[b] *School of Science, Edith Cowan University, Joondalup, WA 6027, Australia*
[c] *School of Engineering and Technology, CQUniversity, Melbourne Campus, VIC 3000, Australia*
[d] *Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Selangor, Malaysia*
[e] *College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia*
[f] *Clearvue Technologies Ltd. Newcastle Street, West Perth, Western Australia 6005, Australia*
[g] *Department of Mechanical Engineering, Graphic Era (Deemed to be University), Dehradun, Uttarakhand 248002, India*
[h] *Centre for Intelligent Systems, CQUniversity, Brisbane Campus, QLD 4000, Australia*

ARTICLE INFO

Keywords:
Hybrid energy system
Low carbon emission
Net-zero buildings applications
Photovoltaics
Sustainable energy

ABSTRACT

The focus of this work is on the optimization of an all-photovoltaic hybrid power generation systems for energy-efficient and sustainable buildings, aiming for net-zero emissions. This research proposes a hybrid approach combining conventional solar panels with advanced solar window systems and building integrated photovoltaic (BIPV) systems. By analyzing the meteorological data and using the simulation models, we predict energy outputs for different cities such as Kuala Lumpur, Sydney, Toronto, Auckland, Cape Town, Riyadh, and Kuwait City. Although there are long payback times, our simulations demonstrate that the proposed all-PV blended system can meet the energy needs of modern buildings (up to 78%, location dependent) and can be scaled up for entire buildings. The simulated results indicate that Middle Eastern cities are particularly suitable for these hybrid systems, generating approximately 1.2 times more power compared to Toronto, Canada. Additionally, we predict the outcome of the possible incorporation of intelligent and automated systems to boost overall energy efficiency toward achieving a sustainable building environment.

Introduction

The building sector is responsible for global energy consumption and related carbon dioxide (CO_2) and other environmentally unfriendly gas emissions. With the increasing population, higher living standards, and climate change, the energy demand is growing almost every day and is expected to increase substantially soon. This highlights the challenges faced by the existing power infrastructures and emphasizes the need for continued research and development in renewable energy areas. The net-zero energy buildings offer a potential solution for achieving sustainable development goals and complying with environmental regulations [1,2]. Currently, the maximum global power consumption is 18.9 TW (Trillion watt) [3], and the energy demand is growing daily. This enormous amount of energy supply mainly comes from burning fossil fuels, which is supposed to be quickly running out soon or over a certain time, if the global energy consumption trends continue to mostly rely on fossil fuel sources. However, with the encouraging current developments seen in new and innovative technologies for harvesting renewable energies and considering the present accelerating trajectory of transition to more renewable and green energy resources, there is a possibility that a good proportion of the already-discovered fossil reserves will remain untouched and kept for the future. However, considering the global decarbonization strategy and the climate goals of the Paris Agreement, in the energy sector, government policies in most of the developed countries at present are more reliant on renewable energy sources for achieving greater sustainability. Global energy consumption has expanded dramatically over the past few decades, primarily as a result of the industrial revolution's consequences and the world's population growth (which is projected to reach over 13 billion

---

* Corresponding author at: Institute of Sustainable Energy, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
E-mail addresses: m.nur-e-alam@ecu.edu.au (M. Nur-E-Alam), aminul.islam@um.edu.my (M. Aminul Islam).

https://doi.org/10.1016/j.seta.2024.103636
Received 14 September 2023; Received in revised form 23 November 2023; Accepted 14 January 2024

Nomenclature

PV	Photovoltaic
BIPV	Building integrated photovoltaic
CBIPV	Colored building integrated photovoltaic
PEDF	Photovoltaics, energy storage, direct current, and flexibility
CO_2	Carbon dioxide
TW	Trillion watt
Si	Silicon
HOMER	Hybrid Optimization of Multiple Energy Resources
TV	Television
Wi-Fi	Wireless fidelity
kW	Kilowatt
GHI	Global Horizontal Index
AC	Alternating current
DC	Direct current
FiT	Feed in Tariff
NPC	Net present cost
LCOE	Levelized Cost of Energy
O & M	Operation and maintenance
LICBC	Low-Income Communities Bonus Credit
MQTT	Message Queuing Telemetry Transport

people by 2050) [3,4]. Rapid industrialization, commercialization, and urbanization are some of the causes contributing to the daily rise in demand for a steady supply of energy. Customers who are residential and commercial users in the building industry use more than one-third of the energy that is distributed globally. Compared to a decade ago, the amount of energy consumed by modern buildings and infrastructure, both residential and industrial, has significantly increased [5,6]. Modern lifestyles and activities, including education to medication, agriculture to industrialization, storage to transportation, and others, are fully required to have an uninterrupted power supply. Also, since the smart city concept has been established, having a continuous and uninterrupted supply of electric power has become the primary objective for metropolitan areas. For the developed world, having a continuous power supply may not be a big issue as there is already enough energy generation (mostly from fossil fuels). Still, for developing countries, it is a big challenge to ensure a sufficient power supply for all. On the other hand, due to the release of glasshouse gases and other pollutants into the atmosphere by non-renewable fossil fuel-based energy sources, urban planners and architects are becoming more and more concerned about the issues of environmental dangers and global warming [6–9]. Therefore, there are no alternatives for power generation except renewable energy sources. However, only one type of renewable energy source may not be enough to produce power towards achieving the energy supply demand without being off-track from the global sustainability goal. Recently hybrid power generation systems have become an attractive option in the renewable energy research areas as they showed the possibility of achieving self-sustained power generation systems for remote and rural areas. However, those hybrid systems are mainly based on multiple renewable power generation systems, including wind energy, solar energy, wave energy, and battery backup systems [9–15]. The goal of a large number of research projects is to produce an optimized hybrid power production system that may minimize the cost of generating electricity in developing nations, isolated locations, or rural or coastal areas. A hybrid power production system, which primarily consists of many renewable energy generation systems, can aid in the development of an integrated and more sustainable strategy for constructing a pathway toward a future free of fossil fuels [14–19]. However, hybrid power generation systems (solar, wind, wave, or others) require big capital investments and abundant land areas. Also, it isn't easy to establish such kind of hybrid (solar/wind or diesel or wave or others) power generation system in the city areas despite the availability of a modern miniature version of wind energy components. Large cities are mainly crowded with many high-rise buildings that block the wind flow and split wind energy into many directions are not suitable for miniature wind turbines. On the contrary, diesel generators and engines are not suitable for city areas as they are very noisy and emit toxic gases, such as CO, CO_2, and others.

Some studies indicate that around 40 % of global energy is consumed by buildings which are in turn putting extra pressure on the energy resources and responsible for greenhouse gas emissions and climate change as well [20–22]. Therefore improving energy efficiency and thus lessening environmental consequences, requires analyzing the energy consumption patterns in buildings. However, besides power generation, energy management is one of the significant factors worldwide in keeping carbon emissions under a specific range and not allowing the global average temperature to be raised by more than 1.5 degrees. Therefore, it is time to think of more alternatives and optimized options to generate power and perform dynamic load management. A hierarchical coordination framework has been conducted by Das, et al, to efficiently manage domestic load profiles by integrating photovoltaic units, battery-energy-storage systems, and electric vehicles resulting in reduced peak period demand on the distribution grid and improved energy efficiency [23]. Another study demonstrated the potential of a general power distribution system of buildings, called PEDF (photovoltaics, energy storage, direct current, and flexibility). The study summarized the feasibility and advantages of having PEDF in buildings and constructions, indicating that it is possible to achieve self-consuming distributed solar generation simultaneously with the option of utilizing a higher portion of the power generated from centralized renewable sources like solar, wind, or hybrid plants [24]. However, enhancing energy efficiency in buildings requires potentially emphasizing multiple things including modern building designs and outdated equipment such as proper insulation materials, efficient heating and cooling systems, and energy-efficient appliances. The problems of obtaining optimal energy performance in buildings also include low awareness and a lack of incentives for energy efficiency which requires a positive boost of behavioral changes and occupant engagement in energy conservation practices. The advancement of technology and the development of innovative building materials, smart energy management systems, and energy-efficient appliances offer diverse ways of saving energy and reducing CO_2 emissions in modern buildings and infrastructures. In addition, insulation, energy-efficient lighting, and coated/glazed windows are some common examples of energy-saving techniques that can be retrofitted into existing structures [25–31]. Integration of renewable energy sources like solar, wind, and geothermal power is of paramount importance in enhancing energy efficiency in buildings and transitioning towards a sustainable energy future. By incorporating renewable energy, buildings can generate their clean energy on-site and thus benefit from having the features of decentralized and low transmission loss enhancing energy resilience. Additionally, by utilizing energy storage technology and renewable energy, buildings can store extra energy for later use, maximizing energy efficiency and lowering peak demand, which lowers operational costs for both owners and occupants.

For urbanization and smart cities, reducing the dependency on the national power grid will be one of the best options for achieving sustainable smart cities by producing energy using renewable energy harvesting sources, mainly solar photovoltaic (PV) systems. Solar PV is one of the most prominent and cost-effective renewable energy systems to mitigate the major challenges in sustainable renewable energy technology developments. There are several types of solar PV systems commercially available in the market. The most common types of PV systems are mainly silicon (Si) solar cells which are primarily effective in generating maximum power if they are installed in a particular arrangement (around 15 ∼ 22 degrees (°) angle with the incident sunlight, depending on the geographic location) [32]. However, currently, they are used in various ways such as vertical walls for building infrastructures though they can generate only up to 70 % of power compared to that installed on rooftops. On the other hand, semi-transparent and colored photovoltaics (BIPV and CBIPV) systems are also getting more privileges to be installed in modern city buildings and infrastructures day by day [33–40]. A highly transparent window-integrated PV system is another ultra-modern PV system that can be used in any modern infrastructure and skyscraper. These solar windows can harvest energy from the sunlight, have a significant impact on the environment, and improve grid security by offering combined energy-generation and saving functionality (because low-emissivity coatings and cutting-edge glass systems have greater thermal insulation capabilities) [37–41]. These newly advanced, highly transparent windows featuring multiple benefits can help reduce carbon emissions and are expected to add momentum to the ongoing effective decarbonization of the building sector's energy use and save money due to low maintenance. Beyond all these available PV systems, it is still challenging to have a fully sustainable infrastructure based on only one type of PV system, either rooftop solar panels or any type of BIPV. Therefore, a combination of different types of PV systems (i.e., rooftop, PV window, and BIPV or CBIPV) installation in modern building infrastructures can ensure maximum energy generation during peak sunshine hours besides offering energy savings features.

In this article, we adopt the idea of a hybrid power generation system and design an all-PV system (including conventional silicon PV panels, transparent solar windows, and colored semi-transparent PV building materials) hybrid power generation system to ensure the maximum energy generation for modern buildings simultaneously to make a small footprint towards achieving a net-zero building in the city areas or suburban areas. We design and optimize two different types of grid-tied hybrid systems using Hybrid Optimization of Multiple Energy Resources (HOMER) software and various types of PV systems based on a specific load requirement for a modelled three-bedroom house. The authors consider the primary meteorological solar radiation data for Kuala Lumpur city in Malaysia as our prime data point for the HOMER Pro simulation processes. Also, we study the measure and collection of the basic meteorological data of solar radiation for many other cities like Sydney, Australia, and Kuwait City, Kuwait, and compare the energy generation possibilities for those cities.

Methodology

Design and motivation of all-PV blended system

The recently become popular hybrid system (usually combines wind, solar, and diesel power generation systems) has proven its advantages over a single renewable power system. The hybrid systems possess several features: fuel saving, lower atmospheric contamination, savings in maintenance, silent systems, and connection to other power supplies, enabling higher service quality than a typical single-source power generation system. However, the main components of hybrid systems are comprised of power sources, storage devices, power management centers, and monitor and control devices, as reported in the literature [42,43]. Fig. 1 represents the schematic diagram of our newly proposed all-solar PV systems-based hybrid power generation system in conjunction with the basic principle, how the hybrid generation system works, and the required components to complete the power generation, saving, and distribution process. In this proposed hybrid system, the conventional rooftop solar modules are designed to be installed on the roof of the building, and conventional windows and other glass panels are meant to be replaced by the modern transparent solar window and preferred, colored solar PV systems.

In recent years, energy cost efficiency has become one of the key factors for sustainable power generation and storage facilities, which stimulates scientists' enthusiasm to introduce more off/on-grid, self-sustainable energy-harvesting, and saving facilities. However, this research aims to deliver the message that it is possible to make the city areas more sustainable and ensure an unremitting power supply for 24 h, 365 days a by being energy-wise and smart in the use of PV technologies.

Simulation and optimization of load consumption, power generation, and cost analyses

Load consumption

In this work, we used HOMER Pro simulation software for our numerical modelling study due to its easy availability, versatile integration capabilities and wide industrial recognition. It offers to model diverse photovoltaic (PV) system configurations effectively, including conventional panels, advanced solar windows, and building-integrated PV systems, and predicts their combined season-dependent and location-dependent performance. This software remains in widespread use in the renewable energy sector, despite some concerns about its accuracy as recently reported in Ref [46]. However, our modelling and blended-

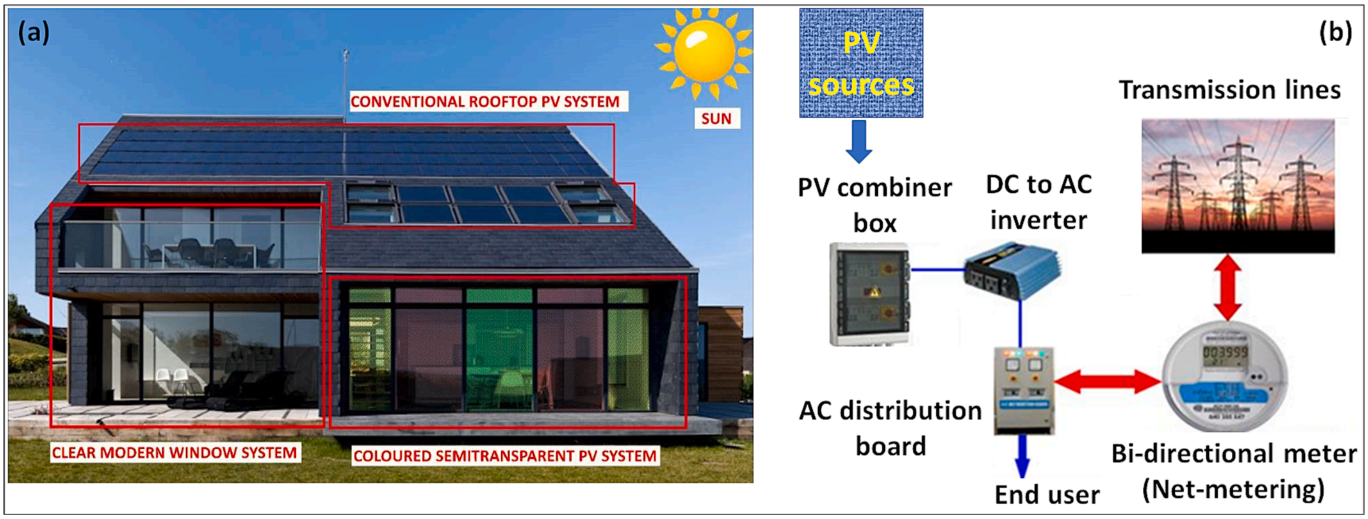

Fig. 1. Schematic presentation of an all-solar PV-based hybrid power generation system in conjunction with the basic operating principle of power collection [44,45].

system optimization results were quite comparable to similar reports in the existing literature [47–51]. To conduct the HOMER Pro simulation, load consumption needs to be considered. We consider a typical three-bedroom unit in the city area. The utility components, quantity, and specification that are used in total power consumption calculation are shown in Table 1. In this calculation, we didn't consider the power consumption for Television (TV) and WiFi modems as they consume a very low amount of power in a year which can be neglected. The total power consumption calculation is given below:

Total power consumption by the unit (per day):

$\Sigma(Power)\ (Usage\ hour)\ (Qty) = 16.612\ kWh/day$

The solar PV system has some electrical losses during power generation. We need to assume a power loss of 30 % to generate efficient power. Hence, the final load demand for the system is:

$Total\ load = (16.612\ kWh) \times (1.3) = 21.596\ kWh/day$

PV panel sizing. Panel generation factor (PGF) is used while calculating the size of PV cells. It is a varying factor depending upon the climate of the site location (depending upon global geographic location). According to research, the average panel generation factor is 3.4 in Malaysia; meanwhile, it varies based on countries due to sunlight irradiation. Hence, the panel capacity for the system is calculated as below:

$$P.C. = \frac{totalload}{panelgenerationfactor}$$

$$= \frac{21.596}{3.4}\ \text{kWh/day} = 6.352\ \text{kWh/day}$$

The total maximum production required by these panels is 6.352 kWh/day during the pick sunlight. Based on the above assumption, three types of panels are selected such as Kyocera KD 145 SX-UFU, Canadian Solar Superpower CS6K-295MS, and CAT 115 W [52–54]. The details of the used solar modules in the optimization process are given in the supplementary file (Table ST1).

Homer pro load profile

In HOMER Pro, the load (kW) input is required to be an average hourly power consumption for each month. In this work, our load input is considered a non-commercial type of load. The monthly average and hourly power consumption throughout the year for a typical building unit is schematically plotted in Fig. 2. Since everyone in the house is asleep between the hours of 0:00 and 5:00, there is a relatively low demand for electricity during this time, and only a few light bulbs, fans, and the refrigerator need to be powered when sunlight irradiation is at its lowest point. The highest load demand is found between 18:00 and 21:00. To satisfy this demand during that time and through the night until sunrise, grid supplies are the only available choice. A significant (albeit gradual) increase in energy demand between 6:00 and 8:00 is connected to morning activities done in preparation for work and school. It is also observed that the demand is comparatively low within the hours of 9:00 to 11:00, and this can be explained by the fact that most people are out of the house for their daily activities during this period. Furthermore, between 12:00 and 2:00, the demand starts to increase rapidly, which can be associated with lunch activities of the household members, before the electricity demand is getting high because all the members of the household are back home and make use of electricity for various domestic and virtual activities. However, during the peak sunshine hours (i.e., maximum power generation) the load demand is moderate, and the load demand can not only be fulfilled from the site-generated power but also possibly provide the excess power to the grid.

Table 1
Description of possible utility units, quantity, and their specification.

Electrical Item	Quantity	Power (W)	W/ Hour	Usage Hour (hr/d)	W-h/ day
Light	10	18	180	4	720
Fan	5	60	300	9	2700
Ventilation Fan	3	30	90	2	180
Fridge	1	120	120	8	960
Electric Hob	1	1200	1200	2	600
Electric Oven	1	3000	3000	0.5	1500
Microwave Oven	1	800	800	0.5	400
Television	3	150	450	2	900
CCTV (6 cameras)	1	48	48	24	1152
Washing Machine	1	1000	1000	2	2000
Tumble-Drier	1	2100	2100	0.5	900
Dish Washer	1	1800	1800	1	1800
Electric kettle	1	1200	1200	0.5	600
Iron	1	1500	1500	1	1500
Vacuum Cleaner	1	1400	1400	0.5	700
	Total	15,188			16,612

Solar irradiance and clearness index

For solar energy-based system utilization, solar irradiance data is crucial. It reveals how much solar energy is incident at a specific spot on the surface of the earth over a specific period. The worldwide extra-terrestrial irradiance ratio on a horizontal plane is what determines the clarity index. The solar global radiation is obtained from NASA's worldwide energy resources database prediction through the HOMER Pro Solar Global Horizontal Index (GHI) resources feature. The data obtained through this source is the monthly average for GHI over 22 22-year period based on the location coordinate introduced to Homer Pro for the location project. This paper's analysis takes part in seven different locations on the earth Kuala Lumpur, Kuwait City, Sydney, Auckland, Toronto, Riyadh, and Cape Town. It can be seen (in Fig. SF1, provided in the supplementary file), that the location of Kuala Lumpur experiences an average solar radiation of 4.91 kWh/m^2 with the same clearness index throughout the year is 0.4910 on a horizontal range surface. With an average of 5.77 kWh per square meter, each day solar irradiance is experienced by Riyadh city where the clearness index is 0.6250 throughout the year. The minimum irradiation among these cities is in Toronto which is only 3.59 with an average of 0.4680 clearness index.

Solar PV modules

In this work, we have used typical flat-plate PV modules as they are capable of generating sufficient power with lowest maintenance. The PV panels are placed toward the south. According to the research, the optimum tilted angle for solar PV panels in Malaysia is between 0 and 15 degrees. We have chosen 15 degrees of the optimum tilt angle during the simulation process. The appropriate angle could not be set for the window and semitransparent PV panels. Hence, different derating factor has been applied for both panel types. For the rooftop PV panel, we consider the Canadian Solar Superpower (CS6K-295MS), and the appraised primary cost of a PV module is $USD 992.00, including installment cost and the replacement cost is $USD 992.00. For the window panel (Kyocera KD 145 SX-UFU) the projected primary cost of a PV module is $USD 1180 including installment cost and the replacement charge is $USD 1180. For semi-transparent glass panels, CAT 115 Watt four panels are being selected with an efficiency of 7.3 % and a derating factor of 70 %. The initial cost is $500 and the installation and replacement cost is $500. All the panels are considered to have a lifetime of around 25 years. Summary of the parameters and the cost of the PV modules is provided in the supplementary file (Table ST2)..

Converter

The proposed all-PV hybrid system is considered a grid-connected

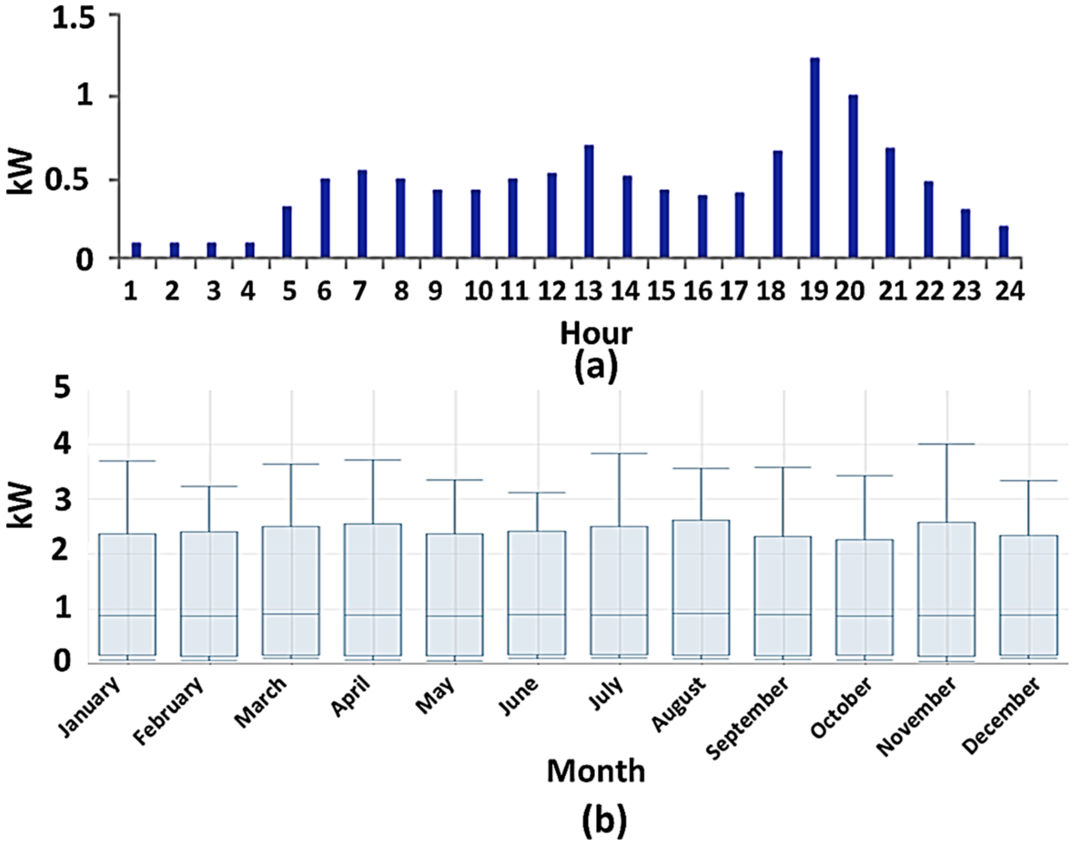

Fig. 2. The schematic representation of daily and yearly load consumption (predicted) profile for a 3-bed room house.

system and the grid provides alternating current (AC) power. However, the PV modules generate the power in direct current (DC) mode, which needs to be converted into AC mode to supply to the users. Therefore, a converter is needed not only to convert an electrical signal from the DC mode to AC mode but also to synchronize the changing signals (of converted AC power from the hybrid systems and the grid) along with supply to load. According to the HOMER suggestion, a system converter is selected for the proposed system during the simulation process (the information about the inverter is detailed in Table ST3). The total estimated price of the converter is around $USD 600/kW including the replacement (if needed) [55]. The system converter rating varies based on power production. For instance, a three-component (rooftop, window, and semi-transparent panel) hybrid system requires a 1.24 kW converter whilst a 1.02 kW converter is enough for a two-component (rooftop and window panel) hybrid system. In addition, the converter rating also varies based on the power production (for example 0.992 for Toronto and 1.28 kW for Cape Town).

Grid

Since it is a grid-connected PV (GCPV) system, the grid power purchase and sell back rates inputs are required to conduct the simulation process. For Malaysia, according to SEDA (2022), Feed in Tariff (FiT) rates for solar PV (Non-individual, $\leq$ 500 kW, 21 years from FiT Commencement Date) scheme and the FiT for solar PV (low voltage category $<$ 1 kV) under the commercial category supply range between 1-kW/month and 200-kW/month, the grid sell back price is USD 0.051/kWh. The power purchase rate for the low voltage commercial tariff category is USD 0.10/kWh [56].

Financial analysis

In this instance, we employed PV panels, a converter, and a utility grid to meet the needs of the load that is provided by an on-grid solar system that is present at the community level. We have done a cost study for the house that can be powered by both sorts of hybrid combinations. Based on the sunlight access, we have categorized the best PV panel selection for rooftop, window, and semitransparent PV modules. At last, we conduct the financial analysis in terms of NPC (the cost of a component includes all the costs of installing and operating the component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime), LCOE (Levelized Cost of Energy measures lifetime costs divided by energy production) and operating coast, risky emissions, PV plate output analysis, etc. Additionally, operation and maintenance (O & M) costs must be included in the overall system cost that is required after the system implementation [57] shown in the Tables below. To continue the simulation process with HOMER Por simulation, we have estimated the capital cost for rooftop PV units as $1170 and about $762 for operation and management. For the window panel, the PV unit cost is $684, whereas the O&M cost is $373.15. The semi-transparent PV panel costs $230 with an O&M cost of $237.87. This estimation has been adopted based on the benchmark of cost breakdown percentage for 1.18 kW Rooftop, 0.580 kW window PV System, and 0.460 kW of semi-transparent glass panel [58].

The economic parameter optimization for each type of PV hybrid system assessed by HOMER Pro software is provided in the supplementary file (Tables ST4 and ST5). The obtained results show that the overall cost for all types of PV systems where the capital cost is higher for rooftop, window, and semi-transparent PV systems than only rooftop and window PV systems. According to Homer Optimizer, the total construction for all three PV systems is $4346.98. However, the total installation cost is less (for two PV systems), as we did not consider the semi-transparent glass PV system in the model. Since the power consumption rate is high during the evening time, the system needs a huge backup from the grid. Moreover, power production from PV also depends on sunlight irradiation. As a result, the maximum power production comes from Cape Town, like Riyadh and Kuwait City, and thus leads to these cities' payback being around 15 years. On the other hand, the lowest production is recorded from Toronto City followed by Auckland. The payback for these cities is around 20 years. However, government subsidies in the renewable energy sector can make these hybrid models more attractive to stakeholders, especially for business investors in the renewable energy market worldwide.

From both Tables above, we can closely observe that the converter cost has been changed as well as the grid cost. The reason behind this is when another Panel type called semi-transparent was added to the system, the power production increased from the PV panel. Hence, the reliability of the grid system has significantly decreased; however, the converter size and price increased at the same time.

Results and discussion

The proposed system's electrical performance has been analyzed based on the sunlight intensity for different cities. Fig. 3 shows the design architecture of the proposed systems. The grid and load are connected to the AC bus since they are 3- phase based AC system. The PV system is designed in and exported from the Homer Pro resources which are connected to the DC bus. An inverter is connected between AC and DC bus to provide AC load. Furthermore, since this is a grid-connected system, no capacity shortage or unmet electric load will be occurred even during the night, on rainy and cloudy days when sunlight irradiation is low, or when the grid/substations must be shut down for maintenance.

Fig. 4 shows the overall production performance of the proposed system for different cities. As we can see the maximum power is generated from the rooftop in all the cities. This study examines the amount of solar power generated through rooftop panels, window panels, and semi-transparent panels, as well as the amount of solar power purchased from and sold back to the grid by each city. The simulated results indicate that the generation of solar power through rooftop PV panels, window PV panels, and semi-transparent PV panels is completely dependent on solar irradiation that varies from city to city. It can be noticed that all these PV components comparatively showed minimum power generation possibilities in Toronto while it is possible to generate higher power in cities like Riyadh and Kuwait City. The amount of solar power purchased from and sold back to the grid by each city is also presented in Fig. 4. For example, Kuwait City purchases 4131 solar power units from the grid, while Toronto purchases 4473 units.

Furthermore, Riyadh sells back 11,404 units of solar power to the grid, while Kuala Lumpur sells back 8365 units. The data provide insights into energy generation from different types of panels and energy transactions in seven cities. The rooftop panels are the most significant energy generation source due to functioning under direct sunlight with the best installation orientation on the roof, compared to PV window panels and semi-transparent PV panels. The grid purchases are found relatively to be low, while the grid sellbacks are relatively high, indicating a surplus of energy in these cities. These data will be useful for policymakers, energy companies, and individuals interested in understanding big cities' energy scenario. The cities like Cape Town, Kuwait City, and Riyadh have almost similar (the highest) production and grid sell-back records. The minimum production has been recorded in Toronto, Canada. This is because the average sunlight intensity on the surface of Toronto is lower compared to others.

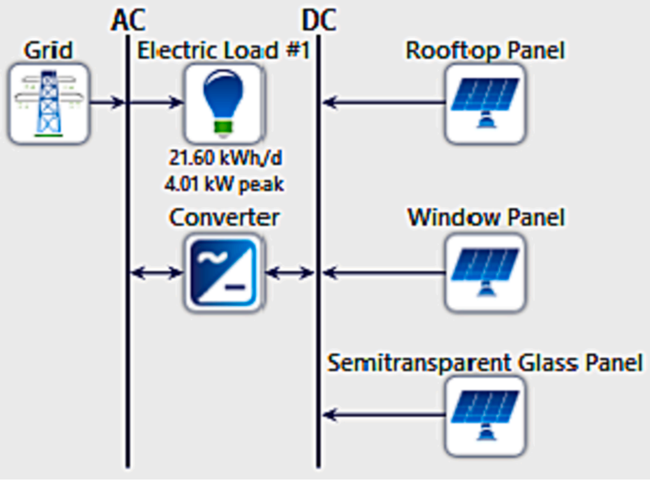

Fig. 3. System architecture schematic of the proposed new all-PV-based hybrid power generation system.

Throughout the year, the overall power generation from the proposed PV-hybrid system for all the cities is presented in Fig. 5. The combination of rooftop, window, and semi-transparent PV sources is shown to be the dominant source to generate adequate power with values ranging from 69.1 in Toronto to 78.9 % in Riyadh, where the "Grid" source is shown to be a secondary source, with values ranging from 20.1 % in Cape Town to 28.4 % in Toronto (Fig. 5a). On the other hand, the rooftop and window PV source combination can generate comparatively less energy and require higher grid backup, as seen in Fig. 5b.

The utilization of renewable energy sources varies significantly among the seven cities. It is clear that cities in the Middle East and Africa, such as Riyadh and Cape Town, tend to have higher green energy production rates. Meanwhile, cities in the Asia-Pacific region, such as Auckland and Sydney, tend to have higher utilization rates of the grid supply. These differences are attributed to various factors such as sunlight intensity and infrastructure.

The maximum output during a peak sunlight hour from all types of panels is 1.17 kWh for rooftop panels, 0.470 kWh for window panels, and 0.373 kWh for semi-transparent panels, whereas the maximum demand is 1.11 kWh (more information is provided in the supplementary file, Table ST6). As a result, the proposed system is capable of fulfilling load demand during peak hours while having an excess amount of power (<2 %) for all types of PV systems. The total panel operation hours are about 4386 h, equivalent to 182 days. The operation hours vary for different cities because of different sunlight hours.

In addition, various gas emission quantities from the hybrid power generation systems for different cities are found very low compared to that of fossil fuel energy generation processes. The amount of gaseous emission per year for other cities varies depending on the system operation hours (though the difference is very small among the cities, more information are summarised in Table ST7).

According to the published reports [21,59,60], progressing towards the goal of net-zero energy 2050 scenario (where the CO_2 emissions by the buildings are projected to be reduced by up to 50 %), demands for having clean electricity generation sources of up to 75 % of the total electricity generation by 2030. Therefore the addition of new clean and green energy sources (up to four times higher than that of today's practice) to the buildings can significantly help to mitigate the expected high energy demand in 2050. However, our simulated results confirm that it is possible to generate up to 75 % of buildings' consumable power from the installed on-site all-solar PV hybrid model simultaneously can achieve lower CO_2 emissions compared to any type of conventional home. The study reveals that our model is technically and economically suitable for any country, especially for very hot and humid climate regions. Fig. 6 presents a visual synopsis of the benefits, drawbacks, challenges, and limitations of all-PV hybrid models.

Overall, all-PV hybrid models offer numerous advantages in terms of renewable energy generation, energy independence, reliability, cost savings, and flexibility. However, they have some drawbacks as well related to initial investment costs, space requirements, intermittent power generation, system complexity, power output optimization due to voltage mismatch and shading effects, and environmental impact. When

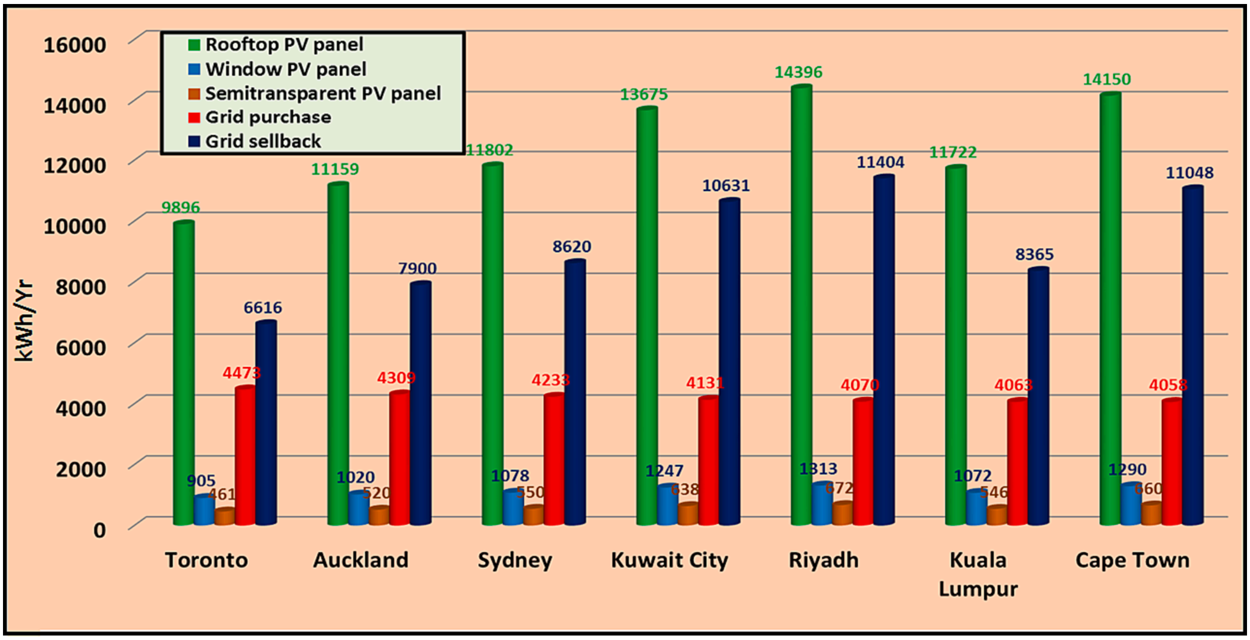

Fig. 4. Power production analysis chart for all types of sources among the cities.

determining the viability of an all-PV hybrid system, it's crucial to carefully assess these variables and take into account certain situations including the national energy policy as well. The discounted rate is suggested by the Homer Pro software. The study is about a performance estimation of the proposed system. In real life, it can vary based on the country's relevant policy applicable at the time. However, selecting the correct discount rate isn't easy because it depends on how people view the investment and its expected risks. Different decision-makers can often have different opinions on what is a good discount rate for their investments. The selection of an appropriate discount rate has long been a central focus in the field of process economics. Valuable insights and guidance on this topic can be found in the Ref [61]. Despite the book's origins dating back to the 1970 s, its contents remain highly relevant, especially in the context of understanding how individual perceptions and risk considerations impact discount rate choices in economic evaluations of industrial processes. This foundational resource continues to be a valuable reference in the domain of process economics. In addition, the PV systems and PV materials (like BIPVs) associated with infrastructures can be considered as building materials that will accumulate value to the property, and householders may have different perceptions and the consequences of the discount rate selection. A comprehensive view of the considerations for the discount rates and their varying perspectives in the framework of household financings are available in Refs [62–64], that can help the homeowner consider when estimating the financial aspects of PV systems. Furthermore, the homeowners can benefit from programs like the Low-Income Communities Bonus Credit (LICBC) which has been recently launched by the U. S. government to expand access to cost-effective and clean energy for underserved communities with tax offshoots for solar and wind projects across the nation. This program offers significant financial incentives (up to a 70 % credit), to qualifying solar and wind projects in low-income communities or on trival land, aiming to encourage clean energy investments and affordable housing development for the benefit of low-income households [63]. Similar types of government, as well as private initiatives worldwide, can encourage the public in general to install smart PV systems or a combined PV system on their property which will boost the race to shape a green future faster.

Integration of IoT and machine learning approach to enhance buildings Sustainability

To construct future sustainable buildings, we have employed the capabilities of a machine learning algorithm to seamlessly integrate our system with the help of the Internet of Things (IoT). This integration facilitates data storage for subsequent analysis and remote monitoring. The employed machine learning algorithm can serve to distinguish the data separately, thus prompting intelligent switching actions [65]. The provided schematic diagram (Fig. SF2) illustrates the architectural layout of the devised configuration system. Within this framework, sensors are one of the key components that establish connections with panels, enabling the real-time monitoring of panel temperature and sunlight intensity. A power sensor is linked to a panel to gauge its power output. The machine learning algorithm operates by analyzing the correlations among power generation, temperature, and sunlight intensity. In case of any anomalies arise an automated smart switch will be activated to shut down the system. Moreover, the air conditioning systems are designed to be deactivated when the inside room temperature reaches 20 °C. Similarly, household lighting and fans are designed to be powered off when human activity is no longer detected.

To achieve this functionality we have considered the ThingSpeak cloud platform as the principal data storage solution. Facilitating data communication between the microcontroller and the cloud, the Message Queuing Telemetry Transport (MQTT) protocol has been adopted, that enables seamless publishing and subscription of data. In order to meaningfully operate the system, it is required to include at least three distinct sensors such as sunlight intensity monitoring sensor (e.g. BH1750), solar panel power assessment sensor (INA219), and the DHT11 and LM35 sensors for tracking panel and indoor temperatures. These sensors are integrated with the NodeMCU microcontroller, facilitating data transmission to the cloud. A list of selected sensors and their technical specification is provided in the supplementary file (see Table ST8).

The schematic illustration depicts the experimental arrangement encompassing both the window panel and rooftop panel setups, accompanied by remote data monitoring through an application as can be seen in Fig. SF3. The outcomes of the experimental configuration are showcased in Fig. 7. Specifically, Fig. 7(a) shows the indoor temperature of the building, while Fig. 7(b) illustrates the corresponding panel

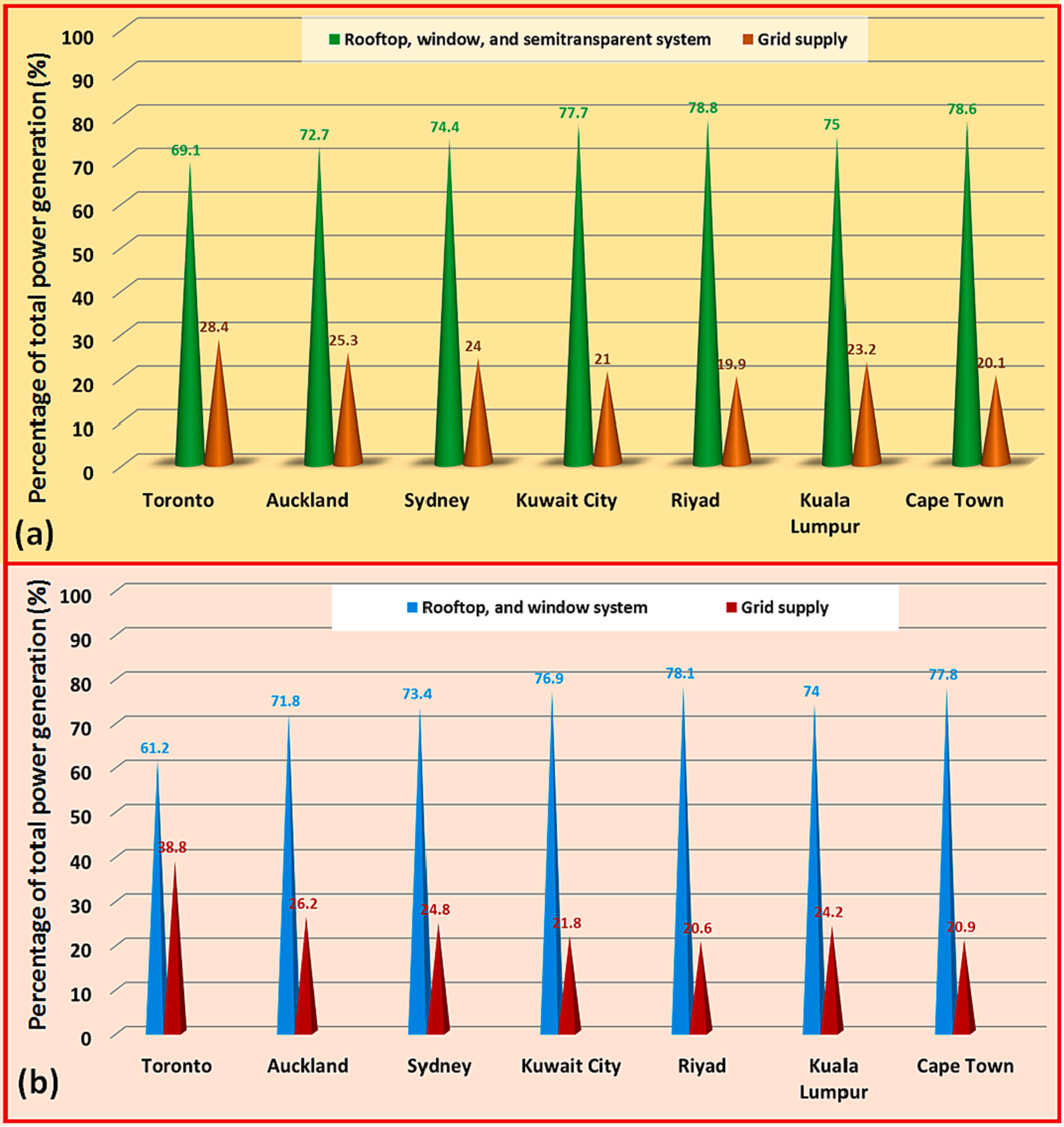

Fig. 5. Percentage of total production from a three-component system vs. two-component system compared with the total amount of energy supply required to form the grid.

temperature reaching 56 °C. Simultaneously, the panel attains a peak power output of 4800 mW, as depicted in Fig. 7(c), and (d) portrays an ascending trend in sunlight intensity, which culminates at 54,000 lx. Furthermore, Fig. 7(b) provides a visual representation of ambient temperature measurements, a critical factor in maintaining optimal equipment temperatures.

Strategic enhancements can be realized by incorporating a sophisticated solar tracking system and optimizing sunlight exposure to achieve peak power generation. Additionally, refining the machine learning algorithm to include a more advanced tripping circuit design capable of promptly responding to unexpected surges in current flow stands as another avenue for improvement. The integration of intelligent automated switches not only augments building sustainability but also amplifies overall energy efficiency. These measures collectively promise a more robust and efficient system poised for future advancements in sustainable buildings and infrastructure development.

Navigating the all-PV blended technology pathway

The exploration of practical considerations and innovative strategies that are steering a transformative path towards sustainability and a clean energy future are needed to achieve the United Nations SDGs goal targeting a certain (small) level of emissions to me achieved by 2030. A specific focus on investigating innovative integration techniques can ensure that renewable energy solutions not only meet functional needs but also enhance the visual and environmental appeal of the structures [66–68]. However, the exploration of the all-PV blended technology evolves with the entire landscape of solar technology integration, where photovoltaics is poised to play a pivotal role in shaping our energy future. The practicality of this all-PV blended technology can be confirmed by the constantly increasing volumes of conventional BIPV markets (where the wall and spandrel-based non-transparent PV modules prevail) and the increasing acceptance of unconventional photovoltaics using high transparency solar window modules, e.g., the systems showcased at Murdoch University Solar Greenhouse [69] and in

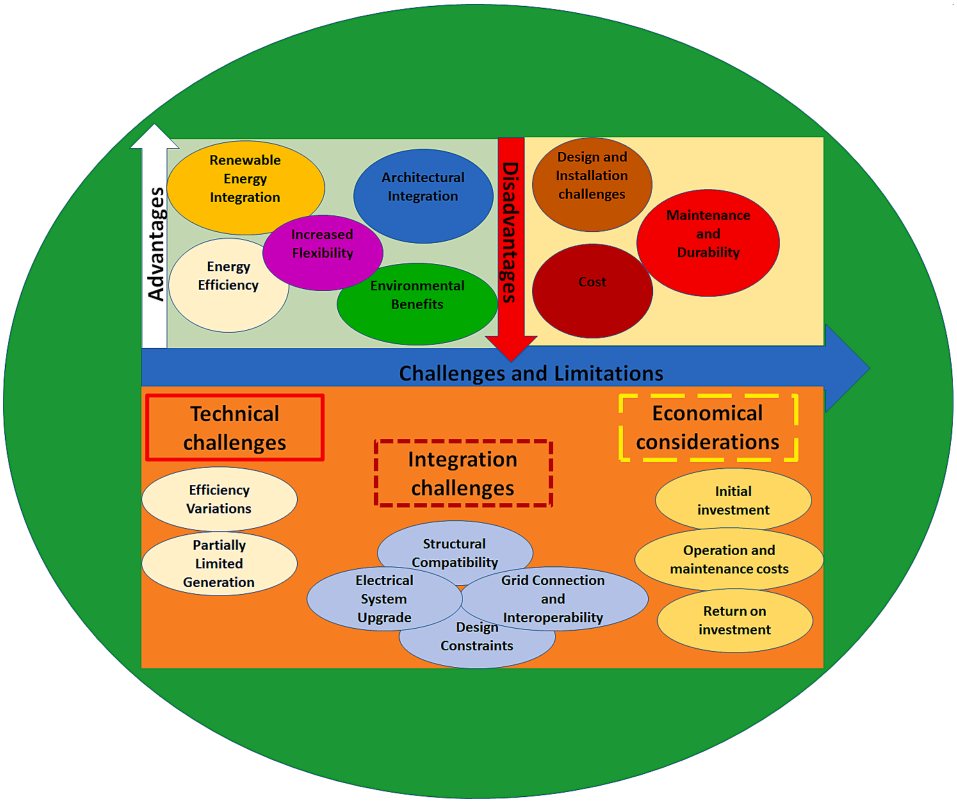

Fig. 6. Schematic of the visual overview of the benefits, drawbacks, challenges, and limitations of all-PV hybrid models. Worth noting that the specific technical challenges, integration constraints, and economic considerations can be varied.

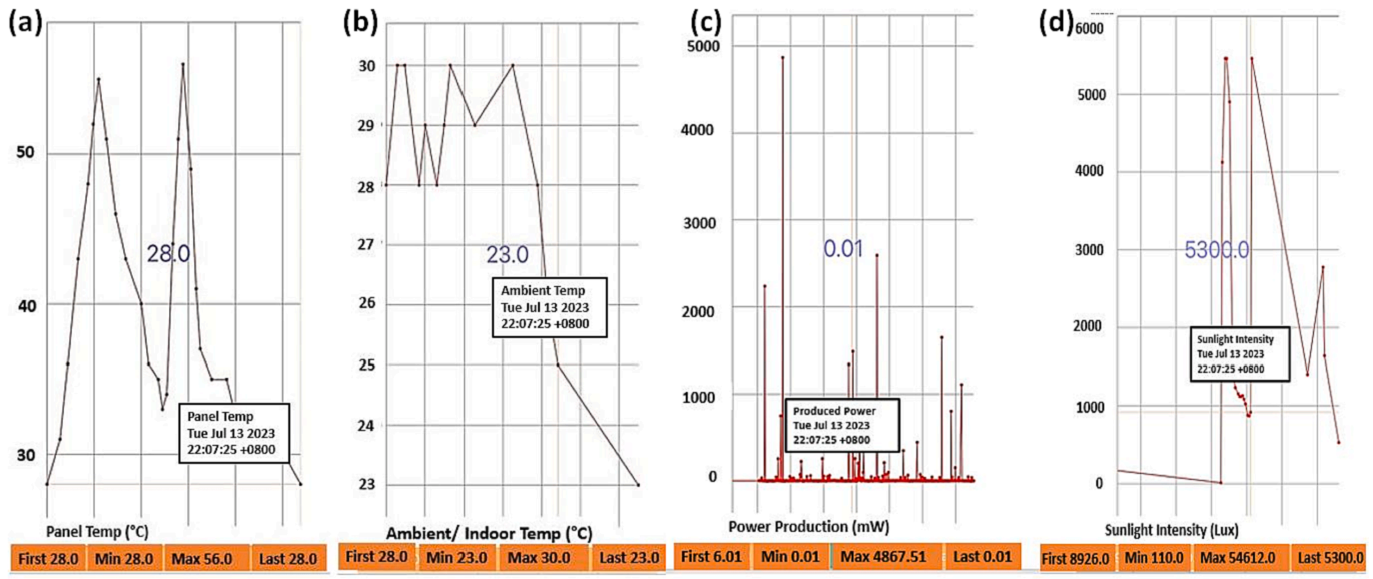

Fig. 7. Schematic overview of solar parameter monitoring through ThingSpeak IoT cloud [65].

Sendai Aqua Ignis Resort solar windows installation built by Tomita Technologies [70]. Therefore, the separate parts of the combined blended PV installation may require to be connected to separate inverter systems, but in terms of overall practicality, these issues are expected to be minor. In our innovative approach, system design, and integration stand as fundamental pillars in the development of PV/BIPV-based hybrid power generation systems. This crucial phase involves tailoring these systems to diverse building types and energy requirements. Therefore, future research work will shift towards selecting appropriate machine learning algorithms for real-time monitoring and control followed by possible installation of prototypes in real-world settings, data collection on energy generation and consumption, and performance assessment to optimize energy utilization and grid interaction based on the available opportunities and funding.

Conclusion

An optimized all-PV blended (hybrid) power generation system has been demonstrated for efficient energy generation and savings on the demand side that can help reduce the dependency on the grid by up to 75 % in a broader sense which is a substitution of fossil fuel. This newly proposed hybrid power generation system that is comprised of conventional solar panels, and advanced solar window systems can hold an important key factor for future sustainable and smart city concepts. In this study, we found that the proposed system is capable of meeting city life power demand during peak hours with an excess amount of power around < 2 %, which can be transferred to the main grid. This study reveals that an all-PV combination (i.e., Rooftop, PV windows, and Semitransparent PV modules) is more effective in generating enough power for most of the cities where more sunshine is available and can significantly improve the city environment. These proposed all-PV hybrid power generation systems can be useful in building modern infrastructures including multi-storied car parks where electric cars can get easy access to charge the battery. However, more research and study need to be conducted to investigate the viability of multiple solar PV energy generation systems, power loss management due to the mismatch of high voltage and current, and the cost-effectiveness of stand-alone all-PV hybrid power generation systems as well as evaluate the performance of ML integration in buildings energy efficiency improvement.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

CRediT authorship contribution statement

Mohammad Nur-E-Alam: Data curation, Formal analysis, Writing – review & editing. **Kazi Zehad Mostofa:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – review & editing. **Boon Kar Yap:** Supervision, Writing – review & editing. **Mohammad Khairul Basher:** Data curation, Formal analysis, Writing – review & editing. **Mohammad Aminul Islam:** Data curation, Formal analysis, Writing – review & editing. **Mikhail Vasiliev:** Formal analysis, Supervision, Writing – review & editing. **Manzoore Elahi M. Soudagar:** Formal analysis, Validation, Writing – review & editing. **Narottam Das:** Conceptualization, Data curation, Funding acquisition, Supervision, Validation, Writing – review & editing. **Tiong Sieh Kiong:** Project administration, Supervision, Writing – review & editing.

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 acknowledge the support provided by Tenaga Nasional Berhad (TNB) and UNITEN through the Ministry of Higher Education of Malaysia (MOHE) with the provided HICoE grant (code 2022002HICOE) at the iRMC of Universiti Tenaga Nasional (UNITEN), and the BOLD Refresh Postdoctoral Fellowships under the project code of J510050002-IC-6 BOLDREFRESH2025-Centre of Excellence and Dato' Low Tuck Kwong International Energy Transition Grant (project code 202203005ETG). The authors also appreciate the academic support from the School of Science, Edith Cowan University, Australia, the School of Engineering, Technology, Central Queensland University Australia, Melbourne, VIC 3000, Australia, and the department of Electrical Engineering, Faculty of Engineering, University of Malaya, Selangor, Kuala Lumpur, Malaysia. Finally, the authors like to thank Mr. Mohammad Rifat Barkot Ullah for his help in drawing images.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.103636.

References

[1] Ahmed Ali K, Ahmad MI, Yusup Y. Issues, impacts, and mitigations of carbon dioxide emissions in the building sector. Sustainability 2020;12:7427. https://doi.org/10.3390/su12187427.

[2] Mardiana A, Riffat SB. Building energy consumption and carbon dioxide emissions: threat to climate change. J Earth Sci Climat Change S 2015;3:001. https://doi.org/10.4172/2157-7617.S3-001.

[3] Statistical Review of World Energy 2022, BP, 2022. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (Accessed on 27/10/2023).

[4] https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html (Accessed on 12/09/2022).

[5] Attia S. Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation. San Diego, CA, USA: Elsevier; 2018.

[6] Basher MK, Nur-E-Alam M, Alameh K. Design, development, and characterization of low distortion advanced semitransparent photovoltaic glass for buildings applications. Energies 2021;14:3929. https://doi.org/10.3390/en14133929.

[7] Kabeyi MJB, Olanrewaju OA. Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Front Energy Res 2022;9:743114. https://doi.org/10.3389/fenrg.2021.743114.

[8] www.uncclearn.org/wp-content/uploads/library/unep207.pdf (Accessed on 14/08/2022).

[9] Altomonte S. Climate change and architecture: mitigation and adaptation strategies for a sustainable development. J Sustain Dev 2008;1(1):97–112.

[10] Rehman S. Hybrid power systems – Sizes, efficiencies, and economics. Energy Explor Exploit 2021;39(1):3–43. https://doi.org/10.1177/0144598720965022.

[11] Alotaibi MA, Eltamaly AM. A smart strategy for sizing of hybrid renewable energy system to supply remote loads in Saudi Arabia. Energies 2021;14:7069. https://doi.org/10.3390/en14217069.

[12] Ghofrani M, Hosseini NN. Optimizing Hybrid Renewable Energy Systems: A Review. In A. F. Zobaa, S. N. Afifi, & I. Pisica (Eds.), Sustainable Energy - Technological Issues, Applications and Case Studies. 2016, IntechOpen. https://doi.org/10.5772/65971.

[13] Jenkins P, Elmnifi M, Younis A, Emhamed A. Hybrid power generation by using solar and wind energy: case study. World J Mech 2019;9:81–93. https://doi.org/10.4236/wjm.2019.94006.

[14] https://www.engineeringforchange.org/news/future-rural-energy-hybrid-renewable-systems/.

[15] Rehman S, Rehman S, Qazi MU, Shoaib M, Lashin A. Feasibility study of hybrid energy system for off-grid rural electrification in southern Pakistan Energy. Explor Exploit 2016;34(3):468–82.

[16] https://arena.gov.au/assets/2018/06/hybrid-power-generation-australian-off-grid-mines.pdf (Accessed on 20/10/2020).

[17] Bose A, Raj k, Kuzeva D, Mura T, Xin J, Jayasuriya J. Hybrid Renewable Power Systems for Generation of Own Power by Small and Medium-Scale Enterprises. E3S Web Conf 2018;61:00011. ICREN 2018, https://doi.org/10.1051 11/e3sconf/201861000.

[18] Dykes, Katherine, King, J.; DiOrio, N.; King, R.; Gevorgian, V.; Corbus, D.; Blair, N.; Anderson, K.; Stark, G.; Turchi, C.; Moriarity, P. 2020. Opportunities for Research and Development of Hybrid Power Plants. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75026. https://www.nrel.gov/docs/fy20osti/75026.pdf.

[19] https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels (Accessed on 10/09/2020).

[20] D Cooper, Energy Efficiency for Buildings, Available online: https://www.euenergycentre.org/images/unep%20info%20sheet%20-%20ee%20buildings.pdf (Accessed on 14 June 2023).

[21] IEA, Buildings, Sectorial overview, Tracking report-2022. Available online: https://www.iea.org/reports/buildings (Accessed on 14 June 2023).

[22] Usman M, Ali M, Rashid T, Ali HM, Frey G. "Towards zero energy solar households – A model-based simulation and optimization analysis for a humid subtropical climate. Sustainable Energy Technol Assess 2021;48:101574.

[23] Das N, Haque A, Zaman H, Morsalin S, Islam S. Domestic Load Management With Coordinated Photovoltaics, Battery Storage and Electric Vehicle Operation. IEEE Access 2023;11:12075–87. https://doi.org/10.1109/ACCESS.2023.3241244.

[24] Liu X, Liu X, Jiang Y, Zhang T, Hao B. Photovoltaics and energy storage integrated flexible direct current distribution systems of Buildings: Definition, Technology review, and application. CSEE J Power Energy Syst May 2023;9(3):829–45.

[25] Pragati S, Shanthi Priya R, Pradeepa C, Senthil R. Simulation of the energy performance of a building with green roofs and green walls in a tropical climate. Sustainability 2023;15(3):2006. https://doi.org/10.3390/su15032006.

[26] H. Riaz, N. Amina, I. Shahbaz, R. Asif, H. Mohsin and A. Irfan, "Green Retrofitting of Educational Building for Enhancing the Building's Performance (Retrofitting of IBM building UET Lahore)," 2023 6th International Conference on Energy Conservation and Efficiency (ICECE), Lahore, Pakistan, 2023, pp. 1-6, doi: 10.1109/ICECE58062.2023.10092496.

[27] Tabadkani A, Haddadi M, Rizi RA, et al. A hierarchical multi-purpose roller shade controller to enhance indoor comfort and energy efficiency. Build Simul 2023. https://doi.org/10.1007/s12273-023-1003-7.

[28] Li Y, Yin W, Zhong Y, Zhu M, Hao X, Li Y, et al. Energy Consumption of Apartment Conversion into Passive Houses in Hot-Summer and Cold-Winter Regions of China. Buildings 2023;13(1):168. https://doi.org/10.3390/buildings13010168.

[29] Albatayneh A, Albadaineh R, Juaidi A, Abdallah R, Zabalo A, Manzano-Agugliaro F. Enhancing the Energy Efficiency of Buildings by Shading with PV Panels in Semi-Arid Climate Zone. Sustainability 2022;14(24):17040. https://doi.org/10.3390/su142417040.

[30] Ji Yeon Hyun. Bo Rang Park, Nam Hyeon Kim, Jin Woo Moon, "Building energy performance of DSSC BIPV windows in accordance with the lighting control methods and climate zones". Sol Energy 2022;224:279–88. https://doi.org/10.1016/j.solener.2022.08.039.

[31] Kim J-J. Solar Technology Integration on Building Façades. The Plan 2022;7(1). https://www.doi.org/10.15274/tpj.2022.07.01.11.

[32] Wilson GM, et al. J Phys D: Appl Phys 2020;53 493001.

[33] Benedicto Joseph, Tatiana Pogrebnaya, and Baraka Kichonge. Semitransparent Building-Integrated Photovoltaic: Review on Energy Performance, Challenges, and Future Potential, Volume 2019 | Article ID 5214150 | https://doi.org/10.1155/2019/5214150.

[34] https://arena.gov.au/projects/monash-university-building-integrated-pv-study/ (Accessed on 20/10/2022).

[35] Awuku SA, Muhammad-Sukki F, Sellami N. Building Integrated Photovoltaics—The Journey So Far and Future. Energies 1802;2022:15. https://doi.org/10.3390/en15051802.

[36] Yunfeng Wang, Ming Li, Reda Hassanien Emam Hassanien, Xun Ma, and Guoliang Li. Grid-Connected Semitransparent Building-Integrated Photovoltaic System: The Comprehensive Case Study of the 120 kWp Plant in Kunming, China, Volume 2018 | Article ID 6510487 | https://doi.org/10.1155/2018/6510487.

[37] Dieter Moor, Victor Rosenberg and Mikhail Vasiliev. High-Transparency Clear Glass Windows with Large PV Energy Outputs, Challenging Glass Conference Proceedings – Volume 8 – 2022 – Belis, Bos & Louter (Eds.), https://www.glassonweb.com/article/high-transparency-clear-glass-windows-with-large-pv-energy-outputs (Accessed on 20/10/2022).

[38] University of California - Los Angeles. "Highly transparent solar cells for windows that generate electricity." ScienceDaily. ScienceDaily, 20 July 2012. www.sciencedaily.com/releases/2012/07/120720135715.htm (Accessed on 18/10/2022).

[39] Transparent Solar Windows, https://encyclopedia.pub/entry/125 (Accessed on 20/10/2022).

[40] Yousef, A. H. Al-Badi, A. Polycarpou. Power management for hybrid distributed generation systems, https://doi.org/10.1080/19397038.2017.1387825.

[41] Vasiliev M, Rosenberg V, Lyford J, Goodfield D. Field Performance Monitoring of Energy-Generating High-Transparency Agrivoltaic Glass Windows. 2023060724 Preprintsorg 2023. https://doi.org/10.20944/preprints202306.0724.v1.

[42] Vladimir Lazarov, Gilles Notton, Zahari Zarkov, Ivan Bochev, Hybrid Power Systems with Renewable Energy Sources – Types,Structures, Trends for Research and Development, In Proc. of Eleventh International Conference On Electrical Machines, Drives And Power Systems (ELMA 2005), 15 – 16 September 2005, Sofia, Bulgaria.

[43] Yogita Bhikabhai, Hybrid Power Systems and Their Potential in The Pacific Islands, https://docs.niwa.co.nz/library/public/SMR406.pdf (Accessed on 20/10/2022).

[44] https://architizer.com/projects/home-for-life/?fbclid=IwAR1jlQECwNcy8dl9C1oL_C7TEoLQtfVPeOHJD4fHXy-dcOey4wLCH5R_WaI (Accessed on 23-May-2023).

[45] Nur-E-Alam M, Basher MK, Iftekharuzzaman MKZ, Islam MA, Haque AHMA, Das N. Rooftop PV or Hybrid Systems and Retrofitted Low-E Coated Windows for Energywise and Self-Sustainable School Buildings in Bangladesh. Solar 2022;2(4):540–58. https://doi.org/10.3390/solar2040032.

[46] Milosavljevic DD, Kevkic TS, Jovanovic SJ. Review and validation of photovoltaic solar simulation tools/software based on case study. Open Phys 2022;20(1):431–51.

[47] Vasiliev M, Nur-E-Alam M, Alameh K. Initial Field Testing Results from Building-Integrated Solar Energy Harvesting Windows Installation in Perth. Australia Appl Sci 2019;9:4002. https://doi.org/10.3390/app9194002.

[48] N. M. Swarnkar, L. Gidwani and R. Sharma, "An application of HOMER Pro in optimization of hybrid energy system for electrification of technical institute," 2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS), Nagercoil, India, 2016, pp. 56-61, doi: 10.1109/ICEETS.2016.7582899.

[49] Q. Hassan, M. Jaszczur, and J. Abdulateef, Optimization of PV/WIND/DIESEL Hybrid Power System in HOMER for Rural Electrification, 2016. J. Phys.: Conf. Ser. **745** 032006.

[50] K. E. Okedu, R. Uhunmwangho, N. Bassey, and R. Azubuike, 'Optimization of Hybrid Energy Efficiency in Electrical Power System Design', Energy Efficiency Improvements in Smart Grid Components. InTech, Apr. 22, 2015. doi: 10.5772/59017.

[51] K. Balachander, G. Suresh Kumaar, M. Mathankumar, A. Manjunathan, S. Chinnapparaj, Optimization in design of hybrid electric power network using HOMER, Materials Today: Proceedings, Volume 45, Part 2, 2021, pp. 1563-1567, https://doi.org/10.1016/j.matpr.2020.08.318.

[52] "Kyocera 145 Watt Black Frame Solar Panel - KD145SX-UFU," EcoDirect. [Online]. Available: https://www.ecodirect.com/Kyocera-KD145-SX-UFU-145-Watt-PV-Panel-p/kyocera-kd145-sx-ufu.htm. [Accessed: 07-Oct-2022].

[53] "Canadian solar SuperPower CS6K-295MS 295W mono solar panel," Solaris. [Online]. Available: https://www.solaris-shop.com/canadian-solar-superpower-cs6k-295ms-295w-mono-solar-panel/. [Accessed: 07-Oct-2022].

[54] "CAT dealer for Mali - Manutention Africaine Mali," Manutafmali.com. [Online]. Available: http://www.manutafmali.com/en/brands-products/cat-product-line/power-systems/electric-power-generation/microgrid/photovoltaic-pv-module-pvt110. [Accessed: 07-Oct-2022].

[55] Nur-E-Alam M, Hoque MN, Ahmed SM, Basher MK, Das N. Energy Engineering Approach for Rural Areas Cattle Farmers in Bangladesh to Reduce COVID-19 Impact on Food Safety. Sustainability 2020;12:8609. https://doi.org/10.3390/su12208609.

[56] https://www3.seda.gov.my/iframe/ (Accessed on 05/10/2022).

[57] Ghazali A, Salleh E, Chin Haw L, Mat S, Sopian K. Feasibility of a vertical photovoltaic system on a high-rise building in Malaysia: economic evaluation. Int J Low-Carbon Technol 2017;12(4):349–57.

[58] Ramasamy V, Feldman D, Desai J, Margolis R. US Solar Photovoltaic System and Energy Storage Cost Benchmarks 2021;Q1:2021.

[59] Santamouris M, Vasilakopoulou K. Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation, e-Prime - Advances in Electrical Engineering. Electr Energy 2021;1:100002.

[60] IEA, Sustainable Recovery, World Energy Outlook Special Report (2020) (Accessed on 14 June 2023).

[61] FOORD (1985) Introduction to Process Economics. Second edition. By F. A. HOLLAND, F. A. WATSON, J. K. WILKINSON. (London: Wiley, 1983.) International Journal of Production Research, 23:1, 223, DOI: 10.1080/00207548508928060.

[62] Giglio S, Maggiori M, Stroebel J. Very long-run discount rates. Q J Econ 2015;130(1):1–53.

[63] Bracke P, Pinchbeck EW, Wyatt J. The time value of housing: Historical evidence on discount rates. Econ J 2018;128(613):1820–43.

[64] Anne Fischer, "U.S. government announces tax credit boost for solar projects serving low-income, tribal communities" October 23, 2023, Available online: https://www.pv-magazine.com/2023/10/23/u-s-government-announced-for-solar-projects-serving-low-income-tribal-communities/, (Accessed on 27 October 2023).

[65] Kazi Zehad Mostofa, Mohammad Aminul Islam, Creation of an Internet of Things (IoT) system for the live and remote monitoring of solar photovoltaic facilities, Energy Reports, Vol.9, Supplement 11, 2023, pp. 422-427, https://doi.org/10.1016/j.egyr.2023.09.060.

[66] Aboelmaaref MM, Zayed ME, Elsheikh AH, et al. Design and performance analysis of a thermoelectric air-conditioning system driven by solar photovoltaic panels. Proc Inst Mech Eng C J Mech Eng Sci 2021;235(20):5146–59. https://doi.org/10.1177/0954406220976164.

[67] Mohamed Abd Elaziz, S. Senthilraja, Mohamed E. Zayed, Ammar H. Elsheikh, Reham R. Mostafa, Songfeng Lu, A new random vector functional link integrated with mayfly optimization algorithm for performance prediction of solar photovoltaic thermal collector combined with electrolytic hydrogen production system, Applied Thermal Engineering, Volume 193, 2021, 117055, https://doi.org/10.1016/j.applthermaleng.2021.117055.

[68] Alhawsawi A, Zayed ME, Moustafa E, Banoqitah E, Elsheikh AH. Hybridizing solar dish Stirling power system with single-effect desalination for sustainable electricity and freshwater co-generation: Mathematical modeling and performance evaluation. Case Stud Therm Eng 2023;45:102997. https://doi.org/10.1016/j.csite.2023.102997.

[69] Vasiliev M, Rosenberg V, Lyford J, Goodfield D. Field Performance Monitoring of Energy-Generating High-Transparency Agrivoltaic Glass Windows. Technologies 2023;11:95. https://doi.org/10.3390/technologies11040095.

[70] "Solar Greenhouses shining at Murdoch University and now in Japan" Available online: https://pr.euractiv.com/pr/solar-greenhouses-shining-murdoch-university-and-now-japan-231976, Access on (31 October 2023).