Energy & Buildings 281 (2023) 112736

Contents lists available at ScienceDirect

Energy & Buildings

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

Assessment of building energy performance integrated with solar PV: Towards a net zero energy residential campus in India

Krithika Panicker *, Prashant Anand *, Abraham George

Department of Architecture and Regional Planning, Indian Institute of Technology Kharagpur, West Bengal 721302, India

ARTICLE INFO

Article history:
Received 30 August 2022
Revised 27 November 2022
Accepted 19 December 2022
Available online 23 December 2022

Keywords:
Energy retrofitting
Energy benchmarking
Energy Performance Index
Renewable energy
Façade BIPV
Solar photovoltaic (PV)
CoVID-19

ABSTRACT

Building Applied Photovoltaics (BAPV) such as Roof-top Solar PV has gained significant attention in recent years for harnessing the untapped potential of renewable energy sources. However, rooftop PV poses hurdles of space restriction and shadowing in densely packed urban residential neighborhoods. This study aims to design and assess the feasibility of an integrated grid-connected Rooftop and Façade Building Integrated Photovoltaic (BIPV) for meeting the energy demand of residential buildings on an academic campus. Three distinctive groups of residential typologies have been investigated in this study, categorized based on built area and occupants' past energy usage. Additionally, the variation in the measured Energy Performance index of the three different residential groups is illustrated to pave the path for the development of a typology-based residential energy benchmarking and labelling system. The Solar PV system has been designed for the maximum household energy demand recorded in CoVID-affected years due to high residential electricity usage in this period. The study showcases that integration of façade BIPV for low-rise residential buildings increases the system energy production to up to 62.5 % based on the utilized surface area for active PV. Furthermore, the Net Zero Energy Building (ZEB) potential for each typology has been achieved by integration of the proposed Solar PV, evaluated as a function of the Energy Performance Index (EPI) and Energy Generation Index (EGI). The designed nominal PV power of the proposed grid-connected plant is 5.6 MW, producing 7182 MWh annually, meeting the maximum residential energy demand in the studied academic campus in CoVID affected year.

1. Introduction

The world's electricity demand has grown at an accelerating rate in the past decade, resulting in an impending energy crisis and high levels of environmental pollution. Driven by economic growth and rising population, US Energy Information Administration (EIA) predicts the global energy demand to increase by 50 % in the next 30 years, with global carbon emissions rising by 35 % over the 2020 levels [1]. This will require a higher contribution of coal, natural gas and, oil in the energy-mix share. Globally, the building sector contributes to 36 % of global energy consumption [2]. With increasing income and population, it is predicted that among non-OECD countries, the electricity use will grow fastest in India, with household electricity use in India predicted to increase more than five times in 2050 compared to 2020 levels [1].

India is the fifth largest economy in the world. This number is an indicator of the magnitude of construction activity taking place in the country, with the manufacturing and construction market in the country being a major contributor to the GDP of the country. With a target economy of USD 5 trillion to be achieved by 2024–25, India is expected to follow an annual growth rate of 9 % for its population of more than 1.3 billion [3]. The building sector in India currently consumes more than 30 % of the total electricity consumption of the country [4]. About 70 % of the total electricity consumed is claimed by residential buildings. As per the Ministry of Statistics and Programme Implementation (MoSPI), the total energy demand for 2018–19 in India from all sectors is 569.5 Mtoe, of which the residential sector consumes 9.1 % (52.04 Mtoe) alone [5]. Further, the domestic sector consumes 24.2 % of the total electricity consumption of the country as of 2019 [6]. With increasing per capita income, and appliance ownership, the electricity consumption in the domestic sector increased from 146 TWh in 2009–10 to 280 TWh in 2018–19 [6]. It is further projected that 769 TWh of electricity and 98.6 Mtoe of energy will be consumed by the domestic sector [7].

India is determined in its efforts to decouple economic growth from GHG emissions to address the global climate change challenge. This is coherent with India's updated Intended

* Corresponding authors.
E-mail addresses: krithika.panicker04@kgpian.iitkgp.ac.in (K. Panicker), prashantanand@arp.iitkgp.ac.in (P. Anand).

https://doi.org/10.1016/j.enbuild.2022.112736
0378-7788/

Nomenclature

AC	Alternating Current
BAPV	Building Applied Photovoltaics
BIPV	Building Integrated Photovoltaics
BIPV	Building Integrated Photovoltaics
DC	Direct Current
DiffHor	Horizontal diffuse irradiation
E_{ARRAY}	Effective energy at the output of the array
EGI	Energy Generation Intensity
EGRID	Energy injected into grid
EPI	Energy Performance Index
gCO2	Grams of carbon dioxide
GlobEff	Effective Global correlation for IAM and shadings
GlobHor	Global horizontal irradiation
GlobInc	Global irradiation incident in actual array plane
IAM	Incidence Angle Modifier
kWh/MWh	Kilo Watt hour/Mega Watt hour
kWp/MWp	Kilo Watt Peak/Mega Watt Peak
Lc	Array Capture Losses
LF	System Losses
MPP	Maximum Power Point
PR	Performance Ratio
PV	Photovoltaics
RH	Relative Humidity
Si-mono	Silicon mono-crystalline
STC	Standard Testing Condition
T_Amb	Ambient Temperature
tCO2	Tons of carbon dioxide
YF	Final Yield
ηpv	PV module efficiency
ηsys	System efficiency

Nationally Determined Contributions (INDCs) goal to attain around 50 % of cumulative installed capacity for electric power from non-fossil fuel sources by 2030 and to decrease the GDP's emission intensity by 45 % from the 2005 figure [8]. To address the energy concerns in the country, the Energy Conservation Building Code (ECBC) was launched in 2007. This was done for the commercial building sector for connected load $\geq$ 500 kW [9]. This code was later revised in 2017 to be compliant with buildings with connected load $\geq$ 100 kW [10]. In 2018, the ECBC code was extended to residential buildings through Eco Niwas Samhita 2018 – Part I for residential projects built on plot area $\geq$ 500 sq.m [11]. The code has been developed to set building envelope performance standards to limit heat gain/loss, and ensure natural ventilation and day lighting. Additionally, the energy efficiency label for residential buildings was also launched in 2019 by the Bureau of Energy Efficiency (BEE) to create a market-driven transformation of energy-efficient residential projects by setting the minimum benchmark to achieve energy-efficient status [12]. Building energy benchmarking is evaluated using the metric Energy Performance Index (EPI), calculated as the total energy consumed in a building over a year divided by the total built-up area (kWh/sq.m/year) [10]. Currently, EPI is mostly discussed in the context of commercial buildings to assess the scope of energy efficiency and improvement [13–15]. However, it should be noted that the rapid increase in residential building stock in developing countries like India, is resulting in increasing electricity usage in the sector [16]. This is associated with the increasing purchasing power of urbanized households leading to the purchase of energy-intensive equipment like air-conditioners in response to improving thermal comfort [17]. Currently, there exists a single climate-based energy-efficiency label for residential buildings in India by the BEE, based on a five-star rating specific to different climates of India specified by the ECBC (Composite, Hot & Dry, Warm & Humid, Composite, and Temperate climate) [12]. The residential energy benchmarking done by BEE however does not account for different typologies of houses in these climatic zones and provides the same standard across all typologies. The Energy Performance Index used by BEE has been given as (Eq. (1)):

$$\mathrm{EPI}\left(\frac{\mathrm{kWh}}{\mathrm{sqm}}\right) = \frac{\mathrm{E1} + \mathrm{E2}}{\mathrm{A}} \tag{1}$$

Here,

E1 = *EPI* for air-conditioned spaces ~25 % area with 24 deg C as set point in (kWh).

E2 = *EPI* for other spaces ~75 % area with natural ventilation set points defined by IMAC (kWh).

A = Built-up Area in sq. metre.

Additionally, Eco Niwas Samhita: Part II has been developed as code compliance for Electro-Mechanical and Renewable Energy Systems by BEE for residential buildings in 2021 [4]. This part stresses the importance of energy performance standards for renewable energy systems, building services,and indoor electrical use. The code has extended for the inclusion of low-rise buildings, as well as affordable housing projects, with carpet areas less than 60 sq.m. This code also provisions a criterion for employing grid-tied renewable energy generation sources in the form of solar and wind energy to meet the energy demand to move towards net-zero energy targets. Environmental and economic repercussions of fossil fuels have driven the need for sustainable and renewable energy technologies [18]. Scientists have paved the path for the advancement of research in the field of renewable energy sources, especially solar energy, due to the rising demand and scarcity in conventional sources [19]. The transition to a decarbonized energy supply that can lower CO2 emissions must be implemented, and PV is an important technology in this regard. Fast expansion in the PV sector is being encouraged by the sharp decline in the price of PV systems and the promotion of legislation to support clean energy technology [20].

Currently India's installed power capacity is dominated by coal with over 204 GW of installed capacity in 2022. The installed renewable energy capacity in India accounts for a share of 39 % in the overall power mix, with solar accounting for 13.2 % of the total installed renewable capacity in India [10]. There is a vast potential for solar energy in India. Being a tropical country, the region receives 3000 hours of sunshine annually, equivalent to 5,000 trillion kWh of solar energy , with most regions receiving 4–7 kWh per square meter [21]. States including West Bengal, Punjab, Orissa, Andhra Pradesh, Haryana, Gujarat, Madhya Pradesh, Maharashtra and Rajasthan have the greatest photovoltaic installation potential due to favorable geographical positions [22]. Government has been proactive in its efforts to establish India as a global leader in solar energy through policy making, technology development, and competitive solar tariff to achieve grid parity. The National Solar Mission (NSM) was launched in 2010 to promote ecological sustainable growth and address India's growing energy security issues. Under this mission, India hopes to have 100 GW worth of grid-connected solar power plants installed by 2022 [23]. Research has shown that grid-connected photovoltaic plants are one of the best renewable energy alternatives to conventional fuels [24]. Moreover, grid-connected solar photo voltaic (PV) plants have evolved at various degrees, spanning in their capacity from small scale to big scale, as a result of the declining cost of solar electric energy [25]. Schemes such as Solar Park theme, VGF theme, Defense Scheme, Grid Connected Solar Rooftop Scheme etc. have been launched to achieve the target of installing 100GW solar power by 2022. The major focus of these programs and target consumers have been solar rooftops.

There are a number of simulation software that have been used by researchers to design, size, and predict the performance of proposed Solar PV systems for different types and scales of usage. Measured data of the PV plants, along with simulation studies are also widely used for performance evaluation of existing PV plants for future operations and predictions.

1.1. Design and performance assessment of solar PV plants using simulation software

The most popular softwares used by researchers to design and simulate solar PV plants are Photovoltaic Systems (PVSyst), System Advisor Model (SAM), Homer Pro, RETScreen, PV Watt, PV Sol, Blue Sol, INSEL, TRANSYS, and PVSOL among others [20,26–28]. Several factors such as module direction, angle, irradiance, temperature, shading, ingress protection is to be considered while designing and simulating the Solar PV Plant [26]. Furthermore, various losses, including both system and array losses affect the efficiency and the final amount of energy injected into the grid from the solar PV modules, and thus should be taken into account in PV design and simulation [20,27]. Another important criterion whilst designing Solar PV panels is the climatic considerations of the study area. Databases such as Meteonorm, National Aeronautics and Space Administration renewable energy resource (NASA) database, and SOLARGIS have been utilised in studies to extract solar radiation and other climatic data for running solar simulations [28–30]. Table 1 gives a summary of studies that have employed simulation software tools to design and simulate solar PV plants at different scales, along with the corresponding predicted performance indicators of energy production and performance ratio (PR) computed from the simulation results.

In addition to the design and simulation of new PV plants, there is significant literature available for the evaluation of the design, components and performance assessment of existing solar PV plants of various scales, technology and capacity. The current study has identified research related to performance assessment of existing plants, supplemented with validation and prediction utilizing various simulation software (Refer Table A1 in Appendix A for the summary of measured versus simulated performance outcomes of studies). A Grid-connected BIPV presented many benefits when the structure, design, orientation and placement of the panels are optimised before installation [35,36]. Further, the addition of BIPV as shading elements on the facade reduces the usage of artificial lighting, and moderates the heating/cooling loads of the building [37]. Literature also showed the effectiveness of BIPV systems for Indian climatic conditions, particularly hot and humid zones [37]. Among the available Photovoltaic technology, crystalline silicon cells have been reported to be more efficient than other materials such as amorphous silicon [38]. They can be further be classified as monocrystalline and polycrystalline, where monocrystalline cells are reported to have higher efficiency when compared with others due to the purity of silicon [39]. Even with lower efficiency and heat tolerance when compared to high-efficiency monocrystalline technology of solar panels [40,41], polycrystalline was the most commonly used material for solar panels across various studies due to its low cost [24,35,42]. Moreover, aspects such as cell type, system cost, size and warranty are used to characterize the solar panel [36]. It is found from the literature study that PVSyst emerges as a superior and trusted tool in predicting energy production of the installed plants with minimum errors and deviations from the measured performance of the solar PV plants and can thus be relied upon for conducting accurate simulations [20,24,43] .

1.2. Objectives of study

This research attempts to address three gaps identified in integration of Solar PV plants in Net Zero Buildings. First, it is seen from the literature that most studies on Solar PV integrated buildings focus on Rooftop solar PV due to its high efficiency, low maintenance costs, attractive tariffs, and subsidy schemes being provided by the government. However, one of the biggest challenges in installing solar panels in roofs of urban residential houses are lack of space due to growing trend of vertical cities, as well as terraces being actively used by occupants resulting in operation and main-

Table 1
Summary of Simulation-based Grid-Connected Solar PV Plant Designs.

Location	PV System Capacity/Type	Software Used	Performance Outcomes	Reference
Pondicherry, India	364 kWp	PVSyst	**Production:** 590 MWh · **PR**: 75–76 %	[28]
Pakistan	3 MWp	PVSyst	**Production:** 4908 MWh · **PR**:83.8 %	[29]
Surabaya, Indonesia	1 kWp	PVSyst RETScreen	**Production:** 1366 kWh · **PR**:73 %	[30]
Kathmandu, Nepal	115.2 kWp	PVSyst	**Production:** 199 MWh **PR**:83.5 %	[31]
Saudi Arabia	100 MWp	PVSyst	**Production:** 1109.7 MWh **PR**:78 %	[26]
Malaysia	1 MWp	PV Watts	**Production**: 1390 MWh **PR**: -	[32]
Tamil Nādu, India	1 MWp	PVSyst	**Production**: Tuticorin (1523 MWh/Year) **PR**:0.75 Madurai (1414 MWh/year) **PR**:0.75 Sivagangai (1335MWh/year) **PR**:0.75 Sivakasi (1398 MWh/year) **PR**:0.75	[33]
Pune (India)	250 kWp	PVSyst	**Production**: 377,502 kWh **PR:**0.764	[34]

tenance issues when installing solar PV panels. Past studies have identified hurdles of installing PV systems in rooftops of commercial buildings, pointing to building services and elements such as parapet walls, staircases, shafts, water tanks, air conditioning units etc. affecting the space availability, maintenance access and causing shading losses on PV panels [44]. Setbacks on the roof are also required in-case of fire emergencies. These obstacles can be evaded by the integration of rooftop solar PV with façade BIPV. The scope of installing façade BIPV as shading elements in residential buildings has not been extensively studied, especially for low-rise and independent residential units.

Secondly, it is observed from the literature study that the installation of Solar PV for academic buildings in university campuses has been widely studied for achieving goals of 'green and sustainable campuses. However, most studies in this respect have been carried out for academic buildings. Nevertheless, residential buildings catering to faculty, and staff occupy a large area in residential academic campuses, and their solar potential cannot be overlooked while designing an energy-efficient educational campus.

Lastly, the study addresses that in addition to climate-based residential energy benchmarking and star rating, there is a need for typology-based residential energy benchmarking in the Indian context to achieve the net zero energy goals of the country. The current study analyses the electricity consumption patterns of 1180 households in the studied university campus, distributed across various building typologies to evaluate the variations in measured energy performance index of the identified housing typologies.

The objectives of the present study are as follows:

- Design and simulation of BIPV system on building rooftop and facade for meeting the electricity demand of the Residential complexes in the Indian Institute of Technology Kharagpur, West Bengal, India.
- Investigating the Photovoltaic Potential of facades of low-rise residential buildings for renewable energy production.
- Evaluate the Net-ZEB potential of different housing typologies based on the measured Energy Performance Index (*EPI*) and Energy Generation Index (EGI) from the proposed PV Plant for each identified housing typology.

The novelty of this work lies in exploring the potential of installing an integrated rooftop and façade BIPV for low-rise residential buildings to meet the maximum recorded energy demand in the last five years, observed in CoVID affected years, and achieve the status of Net-Zero Energy Building. The study also outlines the challenges and performance indicators of designing such system for different scales of consumption and built forms. The study can aid architects, engineers, and home-owners to realize the environmental benefits of installing Solar PV systems for existing households with varying consumption patterns through design and simulation. The current study may inform researchers, architects and occupants about meeting household energy demand, through design of scale-specific Solar PV and achieving the Net-ZEB potential of residential buildings.

2. Methodology

This study aims to design, simulate and assess the performance of a grid-connected photovoltaic system for residential buildings in a university campus. The study employs a 5-step methodology as seen in Fig. 1. Fist, a detailed site analysis has been carried out to analyse the geographic, climatic and zoning analysis of the region, next, quarterly electricity consumption data for the past 5 years have been obtained and analysed for the entire residential population of the campus. In the third step, a Solar PV system ideal for the current project has been designed through various input parameters based on field survey and thorough literature study. In step 4, simulation of the designed system has been carried out in PVSyst software using performance assessment parameters. Finally, in step 5, the performance of the designed Solar PV Plant is compared against the energy demand of the studied buildings, and the Net ZEB potential of the studied buildings have been assessed. .

2.1. Study area

Kharagpur is located in the Paschim Medinipur district of West Bengal, India at Latitude 22°21′00″ North and Longitude 87°20′06″ East. Kharagpur has an elevation of 61 m from sea level. The studied university campus – The Indian Institute of Technology (IIT) Kharagpur is a public research university established by the Government of India, located in Ward No. 30 of Kharagpur region. Climate of Kharagpur can be classified as sub-humid, subtropical. Meteonorm 8.0 is used to extract the climatic details of the study area. Fig. 2 shows the relationship between the monthly temperature profile and global irradiation for Kharagpur, India. The average ambient temperature annually is 26.4 °C, with the highest recorded temperature 31.4 °C in May and lowest recorded temperature of 18.7 °C in January. The average annual wind velocity is 1.1 m/s, with highest recorded velocity of 1.6 m/s occurring between April to May, and the average annual relative humidity is 0.720. The annual average global irradiation is 4.49 kWh/m^2/day with the highest recorded as 5.82 kWh/m^2/day in May and lowest irradiance recorded as 3.52 kWh/m^2/day in December. The Global Horizontal Irradiance annually is 1637.6 kWh/m^2/year, and the Diffused Horizontal Irradiance annually is 943.1 kWh/m^2/year.

2.1.1. Types of residential units

The studied university campus covers an area of 2100 acres, out of which the existing staff, and faculty (non-student) residential zones occupy an area of approximately 250 acres. There are a total of 15 residential blocks in the campus, this figure is projected to increase with future expansion plans of the university. For the current study, 8 residential complexes have been identified and studied. The 8 residential complexes have been classified into three groups based on built area as shown in Fig. 3. The electricity consumption pattern, building layout, roof plan and usage, façade area, and contextual details of these complexes have been analysed. The built area versus electricity consumption of the 8 residential complexes, and subsequent groups can be observed from Fig. 4.

Most of the student hostels as well as few academic buildings in the studied university have already been equipped with large-scale grid-connected Solar PV panels. On discussion with the university employed engineers, it was discovered that the residential quarters for staff and faculty have not been considered for Solar PV installation due to certain functional constraints such as unavailability of spare terrace area (human, electrical, mechanical operation), shading due to trees, single storey bungalows, and other technical hurdles such as uncertainty in electricity consumption load profile of households. Fig. 4 shows the typology-wise annual average household electricity consumption based on the built area of each type of building. Three groups of typologies with similar consumption patterns have been identified for the study. Homogeneity in built area within each group is also observed. Group A, B, and C corresponds to 1 BHK low-rise apartment, 2 BHK low-rise apartment, and 3–4 BHK independent bungalows respectively. For Group A, 12 households (1 BHK) contribute to one block with a total of 40 such blocks on campus, 6 Households (2 BHK) contribute to one block of Group B with a total 30 blocks on campus, and independent one storeyed

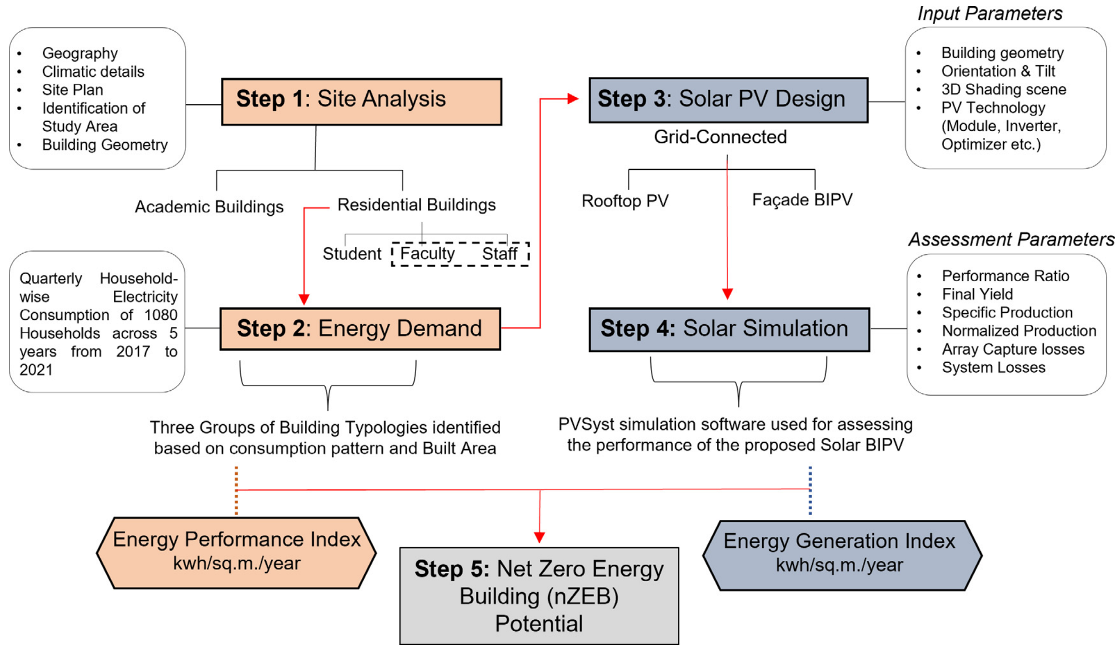


Fig. 1. Methodological framework for the current study.

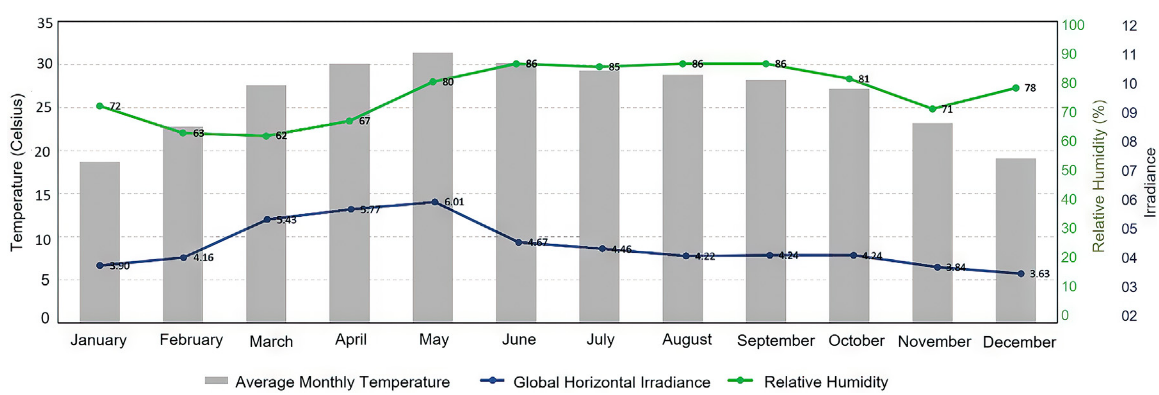


Fig. 2. Monthly temperature and Relative Humidity vs Irradiance levels in Kharagpur, India.

bungalow correspond to Group C, with a total of 388 of typology C buildings in the campus.

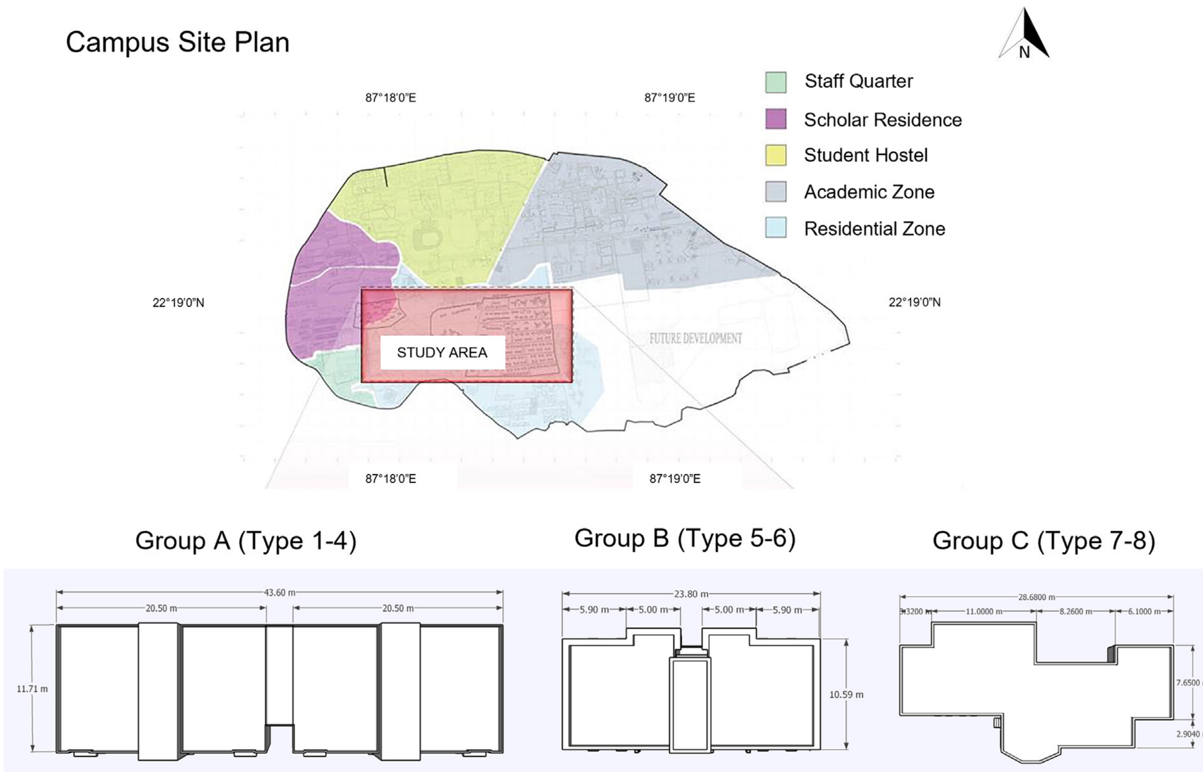
2.2. Data collection

Residential electricity consumption data has been obtained from the university records for a period of five years from 2017 to 2021. The electricity consumption data is in the form of kWh/-household/quartile, where each household has four data points distributed across four quarters (January-March, April-June, July-September, October-December). There are five kinds of errors in the dataset: faulty readings, duplication of households, blank (Not Available) entries, zero entries, and inconsistency between households in the four quartiles. Microsoft Excel has been used in the dataset cleaning process. Two VBA macros have been developed in Microsoft Excel to clean the available dataset. Finally, the electricity consumption for 1180 households has been studied across five years for uniformity in comparison.

Fig. 5 depicts the quarter-wise Total Residential Electricity Consumption of the campus across five years. The annual residential electricity consumption has seen a rising trend from 2432.95 MWh in 2017 to 3197.4 MWh in 2021. The residential electricity consumption in 2020 is the highest recorded accounting to 3227.9 MWh. The 8 identified residential units have been grouped into three categories (Group A,B, and C) according to electricity usage and built area as shown in Fig. 3 and Fig. 4. The maximum electricity consumption of each group has been identified using the available data set for Covid affected year - 2020. For Group A, 12 households (1 BHK) contribute to one block with a maximum annual electricity demand of 22.7 MWh/block/year, 6 Households contribute to one block of Group B with a maximum annual demand of 24.3 MWh/block/year, and independent bungalows (3 BHK) corresponding to Group C consume a maximum of 13.83 MWh/household/year.

2.3. PV system design

A schematic diagram of the proposed grid-connected solar PV is provided in Fig. 6. Grid-connected Photovoltaic plants are those in which the Photovoltaic assembly are connected to the grid by a power inverter, allowing them to operate parallelly with the grid [45]. The energy needs during non-sunlight hours



Typology	Group A (Type 1-4)	Group B (Type 5-6)	Group C (Type 7-8)
No of houses per block	12 Houses in 1 block (multi-dwelling) (1 BHK)	6 Houses in 1block (multi-dwelling) (2 BHK)	Single dwelling bungalow (3-4 BHK)
Built Area per household	<70 sqm built area per household	70-90 sqm built area per household	90-180 sqm built area per household
Roof Area	410 sqm.	265 sqm.	230 sqm

Fig. 3. Site Plan of university campus highlighting the studied Residential Blocks.

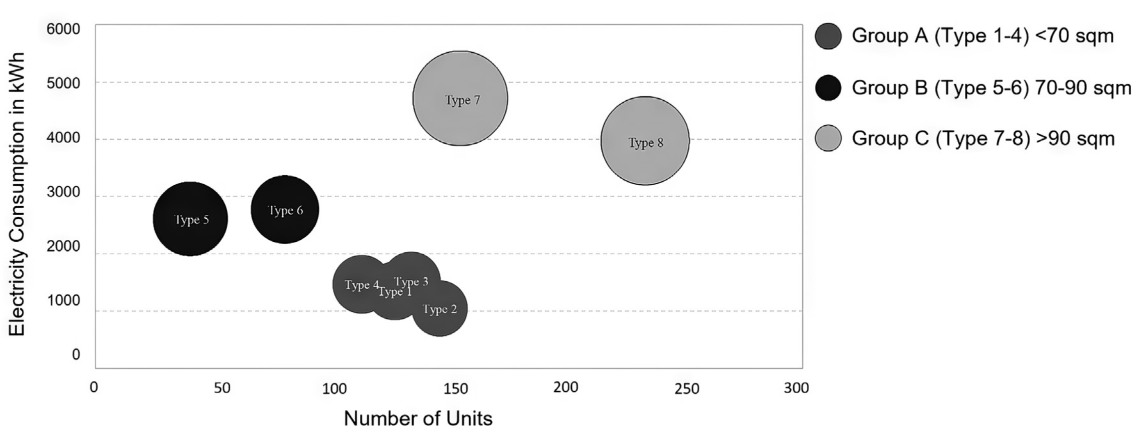


Fig. 4. Identification of Residential Typology groups based on Electricity Consumption and Built area.

are met by the local grid. The components of the PV system include photovoltaic panels connected to power optimizers and maximum power point trackers (MPPT) to maximise and optimise the DC power generated by the solar PV array [46], solar inverter, and bi-directional net meter that allows utility customers to offset their electrcity usage with self produced electricity from PV systems, and send the the excess energy to the utility grid that can be sold at retail price [47].

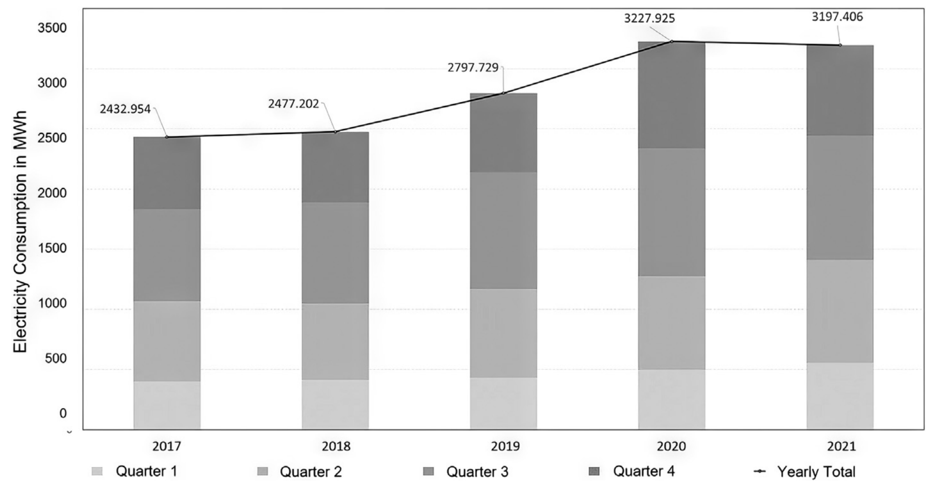


Fig. 5. Total Residential Electricity Consumption of studied university campus over 5 years from 2019-2021.

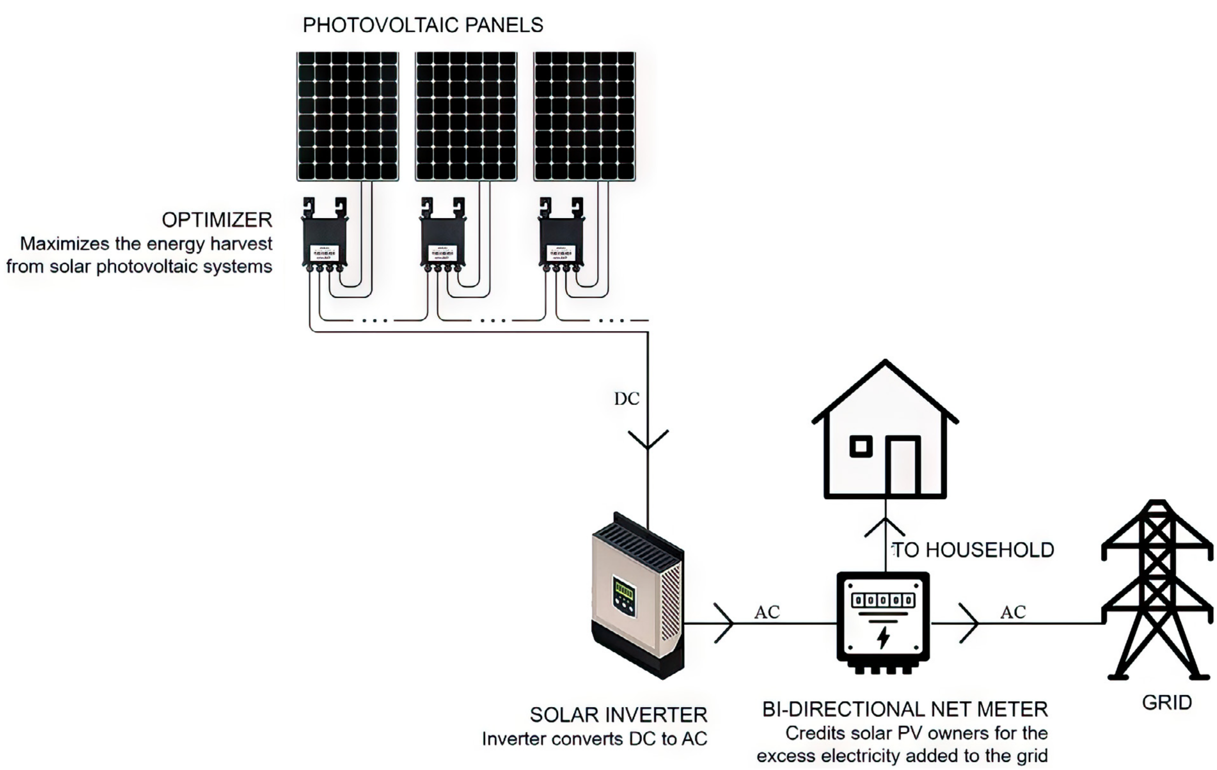


Fig. 6. Schematic diagram of the proposed grid-connected solar PV system.

2.4. Simulation using PVSyst software

2.4.1. Input parameters for PVSyst

A computer simulation tool called PVSyst has been used to investigate, categorise, and analyse data of the proposed solar photovoltaic systems. The program allows the design and assessment of grid-connected, standalone, and DC-grid solar photovoltaic systems. PVSyst performs monthly yield analyses, load profiles, and anticipated system costs [32]. PV systems with several orientations and tilt, as well as inverter type can be concurrently modelled on the software. It utilizes the one-diode PV model, to calculate the performance of the designed solar PV technology. The solar and weather data is provided based on an interpolation method from Meteonorm DLL, or the closest point method from the NASA-SSE database [48]. PVSyst tool allows for the definition of precise system parameters and evaluates impacts of phenomenons such as thermal behaviour, wiring, module quality, incidence angle losses, and partial shade of nearby objects on the array [49,50]. The software utilises performance parameters such as performance ratio (PR), specific production (kWh/kWp/year), normalised production (kWh/kWp/day), Array Collection Losses (Lc) (kWh/kWp/day), System loss (Ls) (kWh/kWp/day), and Produced Useful Energy (Yf) (kWh/year), to analyse the performance of the designed PV plant. The present study uses PVSyst 7.2 to design and simulate the grid-connected PV system. These are the input parameters for the software:

- Orientation and Tilt Angle

Fig. 7 shows the inclination and orientation for the proposed solar panel. Literature studies suggested that the tilt angle for the PV array should correspond to the latitude of the location to get the maximum solar irradiation [51]. The latitude of the study area is 22°21′00″ North; thus, the corresponding tilt angle should be 22°. This is verified by running the PVSyst optimization tool for orientation and tilt for ideal rooftop PV location, where the maximum global irradiance is obtained at 22.2° and 0° azimuth . In the northern hemisphere, the solar panel should be tilted towards the South. The rooftop solar PV is thus placed on a canopy structure at a tilt of 22° facing South (true Azimuth).

The design and placement of the façade BIPV was done to maximise the production and performance of the panels for the specific studied buildings. The main factors considered were the façade orientation, tilt and shading. It can be observed from Fig. 8(a) that Southern façade provides the maximum array output, while the PV placed on the North façade produces 35 % lesser energy compared to South. Furthermore, changing the angle from 22° to 30°, improved the PV output by 13 % (Fig. 8(c)), in contrast to a 33.4 % drop in energy generation when the panels are placed vertically at 90° (Fig. 8(b)). It can also be seen from Fig. 8(c), that the PV should be designed to avoid shadowing to increase output. Providing additional layers of PV on top may produce more energy than splitting into two rows, but the design and weight of the structural system to support the PV modules should be considered while designing. For the present study single layer PV array (single and multi-row configuration according to building form) on the Southern façade at a tilt of 30° has been considered as the optimal case.

- **System Design and Detailed Losses**

Table 2 shows the system design of the proposed on-grid Solar PV system, along with detailed losses including loss due to ohmic resistance at wiring circuit at AC and DC, soiling loss due to dust accumulation on cells, thermal loss due to cell temperature, and other array and system losses. The PV modules used are manufactured by LG electronics, containing 60 cells (6 X 10) of monocrystalline silicone in tempered glass with anodized aluminium frame. Inverters with 8 kW and 6 kW capacity along with Solar power optimizers manufactured by SolarEdge has been utilised for the study. Power Optimizer is a DC/DC converter, that is connected by installers to each solar module. The optimizer can increase system energy production by tracking the Maximum Power Point (MPP) of each solar module.

2.4.2. Design of PV system for Group A, B and C

Two cases have been described for each of the groups corresponding to 1) Rooftop Solar PV, and 2) Integrated Rooftop and Façade BIPV. Case 1 describes the Rooftop Solar PV plant, where the panels have been placed on a canopy structure on the roof at a height of 2.1 m, tilted at 22°, and facing South. The canopy structure allows placement of solar PV on building roofs that are operational and have inadequate space for roof BAPV placement. In Case 2, an integrated system consisting of the rooftop solar PV panel, along with BIPV for façade, designed as a shading element at an angle of 30°, facing South has been proposed. The available roof area of one block of Group A is 410 sq.m. Group B is 265 sq.

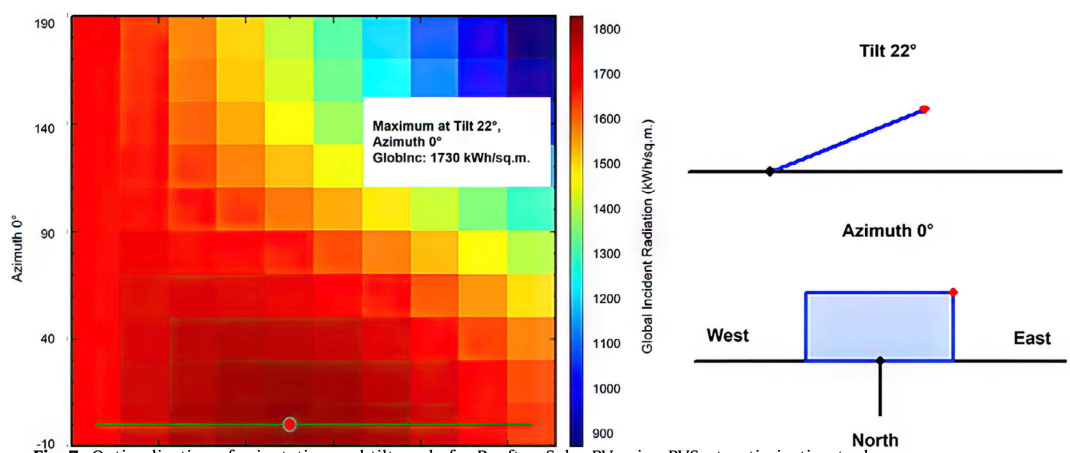


Fig. 7. Optimalization of orientation and tilt angle for Rooftop Solar PV using PVSyst optimization tool.

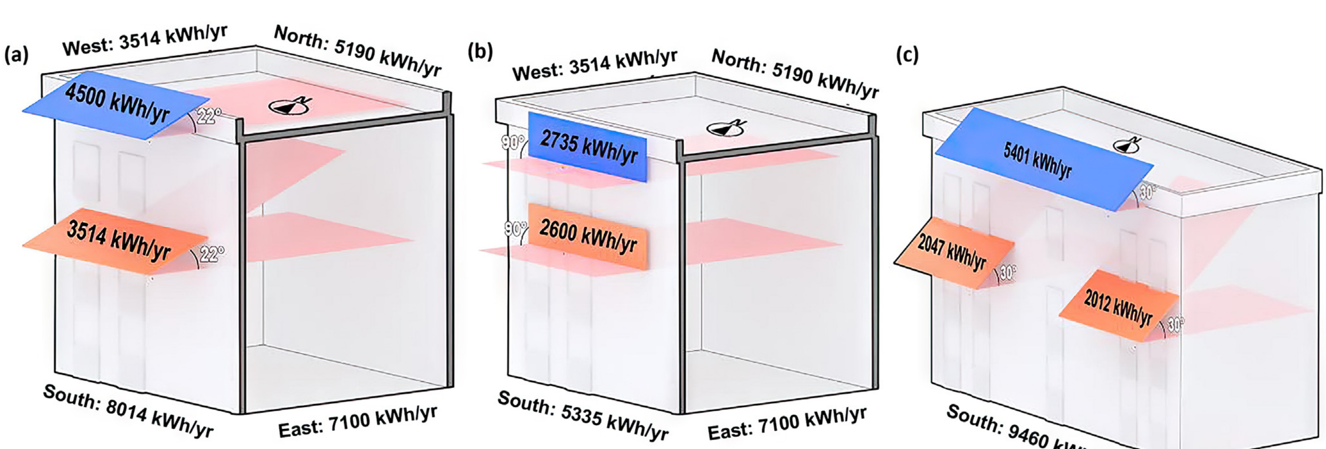


Fig. 8. Determination of optimal orientation and tilt of Façade Solar PV placed at (a) 22°; (b) 90° and (c) 30°.

Table 2
Solar PV System Specifications.

Parameter	Details
PV Module Make	LG Electronics
Module Technology Used	Mono Crystalline Silicon
Module Dimension	1.768 m X 1.042 *m*
Module Weight	18.50 kg
Module Peak Power (Pmax)	440 WFP
Maximum Voltage (Vmpp)	36.7 V
Maximum Current (Impp)	10.56 A
Open Circuit Voltage (Voc)	54.3 V
Short Circuit Current (Isc)	11.06 A
Inverter Make	SolarEdge
Optimizer Make	SolarEdge
Detailed Losses	
Thermal Loss factor (Constant) (cell temperature of module)	20 W/m^{3}K
Ohmic Loss DC (Loss fraction at STC) (Wiring loss)	1.5 %
Ohmic Loss AC (Loss fraction at STC) (Wiring Loss)	0.91 %
Module efficiency Loss (material, environmental factor, PV system devices)	0.8 %
Power Loss at MPP (electrical mismatch loss)	2 %
Soiling Loss (dust, grime on panels)	1.5 %

m., and Group C is 230 sq.m. Taking into account equipment, occupant use, and shadow analysis, around 40 % of the roof space has been considered for placing the solar panel on the roof. Details regarding the six systems for the three groups are given in Table 3. The shading by trees and neighboring buildings for each typology group has been considered for the study based on field investigation to run detailed shadow analysis in the 3D scene and incorporate the resulting array capture losses.

2.4.3. Carbon emissions reduction

The installation of solar panels decreases the CO_2 emissions by replacing environmentally harmful conventional energy sources with renewable ones. PVSyst simulates and analyses the CO_2 emissions saved by installing the PV system through a CO_2 emission balance sheet. It employs the Life Cycle emission (LCE) tool that represent the emissions of CO_2 associated to a given component or energy production. The total carbon balance for PV installation depends on four key factors: the system production (or yield), system lifetime, Grid LCE (given in gCO_2/kWh) and PV system LCE (given in tCO_2). The emissions per unit electricity (generated by conventional fuels) is estimated to be 805.8 g$C0_2$/kWh by the International Energy Agency (IEA) [52]. For the current study, the PV system lifetime has been considered as 30 years, with an annual degradation of 1 %.

3. Results and discussion

In this section, the simulation results generated from PVSyst for the proposed photovoltaic system have been presented. Performance parameters such as produced energy, specific production, performance ratio and system losses have been computed for each case. The obtained results will be analysed for evaluating the performance of the proposed PV system against the maximum electricity demand of each typology.

3.1. Electricity consumption pattern in residential units of the campus

Fig. 9 shows the quarterly electricity consumption from 2017 to 2021 for the 8 types of houses identified on campus. Quarter 3 (July to September) sees the highest consumption of 874.2 MWh with almost 113 % more consumption when compared to Quarter 1 in the pandemic affected year of 2020. According to Meteonorm 8.0,

Table 3
Description of PV System Components for different typologies.

Technical Specification	GROUP A		GROUP B		GROUP C	
	Case 1(a): 10.6 kWP	Case 2(a): 17.6 kWp	Case 1(b): 10.6 kWP	Case 2(b): 21.1 kWp	Case 1(c): 7.0 kWP	Case 2(c): 11.4 kWp
Plant DC Capacity (Nominal)	10.6 kWp	17.6 kWp	10.6 kWp	17.6 kWp	7.0 kWp	11.4 kWp
Maximum PV Power	10.3 kWDC	17.2 kWDC	10.4 kWDC	17.4 kWDC	6.9 kWDC	11.2 kWDC
Nominal AC Power	8.0 kWAC	14.0 kWAC	8.0 kWAC	16.0 kWAC	6.0 kWAC	8.0 kWAC
Module Quantity	24	40	24	40	16	26
Module Area	48 sq.m.	80 sq.m.	48.2 sq.m.	80.0 sq.m.	32 sq.m.	52.0 sq.m.
Inverter Quantity Used	8 kW X 1No's	8 kW X 1No's, 6 kW X 1No's	8 kW X 1No's	8 kW X 1No's, 8 kW X 1No's	6.0 kW X 1No's	8 kW X 1No's
Optimizer Capacity	440 W	440 W	440 W	440 W	440 W	440 W
Module Tilt	22°	22-degree, 30°	22°	22-degree, 30°	22°	22-degree, 30°
Azimuth	0 (True South)	0 (True South)	0 (True South)	0 (True South)	0 (True South)	0 (True South)
MMS Orientation	Landscape	Landscape	Portrait	Portrait, Landscape	Landscape,	Portrait, Landscape
String Module Configuration	MPPT 1–8 No's and 3 string	MPPT 1–8 No's and 3 string MPPT 2–16 No's and 1 string	MPPT 1–8 No's and 3 string	MPPT 1–8 No's and 3 string MPPT 2–8 No's and 2 string	MPPT 1–8 No's and 2 string	MPPT 1–8 No's and 2 string, 10 No's and 1 string
Total No. of Strings	4 No's	4 No's	3 No's	5 No's	2 No's	3 No's
No. of Strings per Inverter	4 No's	3 No's and 1 No's	3 No's	3 No's and 2 No's	2 No's	3 No's
No. of Modules per Inverter	24 No's in Series	24 No's and 16 No's	24 No's in Series	24 No's and 16 No's	16 No's in Series	26 No's

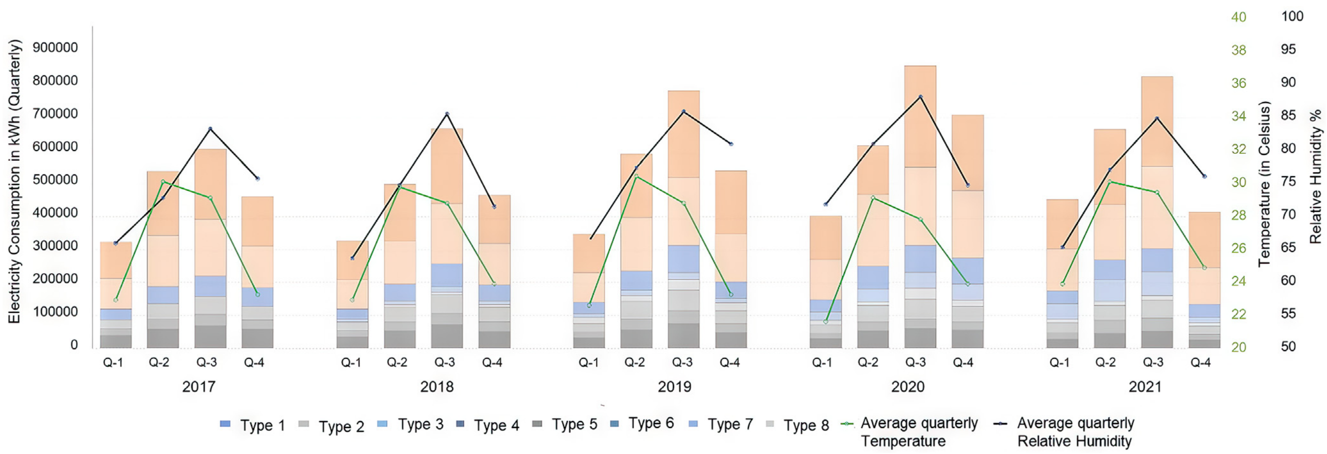
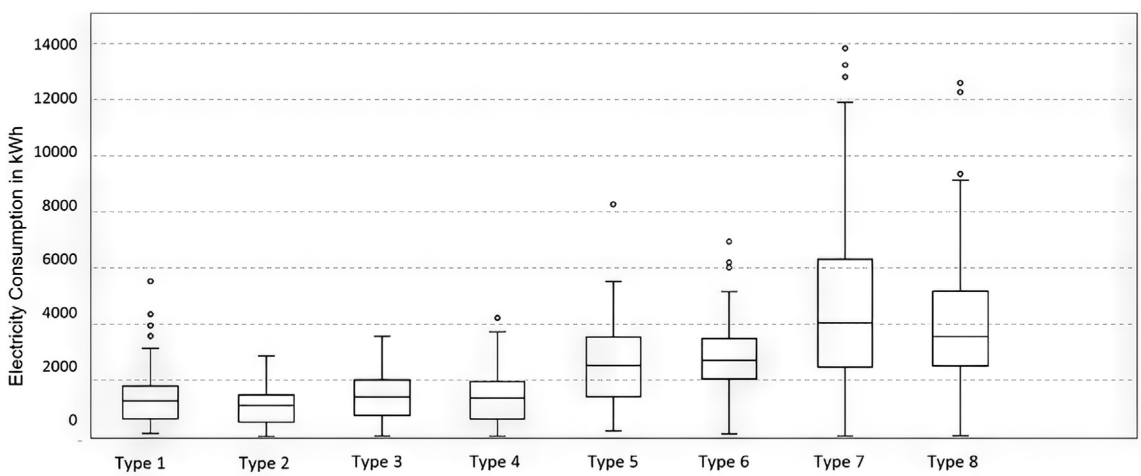
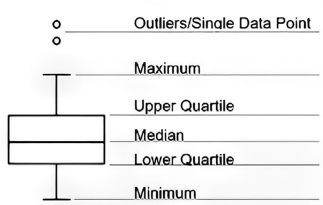


Fig. 9. Typology wise quarterly electricity consumption from 2017 to 2021.





		Minimum	Lower Quartile	Median	Upper Quartile	Maximum
Type 1	Group A (1 Block = 12 Household)	224	707	2729	1821	3134
Type 2		206	635	1160	1523	2715
Type 3		213	934	1446	2023	3570
Type 4		250	766	1468	1974	3725
Type 5	Group B 1 Block = 6 Household)	459	1483	2525	3550	5521
Type 6		409	2057	2720	3506	5161
Type 7	Group C Single Household	211	2628	4086	6349	11918
Type 8		240	2518	3563	5174	9120

All Values in kWh/Household/Year

Fig. 10. Typology wise Annual Electricity Consumption per household.

climatic data input, the highest level of relative humidity (0.805 – 0.841) is recorded in the third quartile between July to September, through the temperature in third quartile (29.3 °C – 28.2 °C) is slightly lower when compared to second quartile (31.4 °C – 29.3 °C). The thermally uncomfortable conditions correspond to the high household energy usage in the third quartile. Moreover, the total residential energy demand increased from 2432.9 MWh/year in 2017 to 3197.4 MWh in 2021. The highest residential electricity consumption was seen in pandemic affected year – 2020, with a consumption of 3227.925 MWh/year. The highest energy consumption during 2020 is mainly due to CoVID pandemic when peoples were forced to spend maximum time indoors, thus, resulting in increased operation of energy-intensive appliances.

The annual electricity consumption for each typology for the pandemic affected year 2020 is given in the form of a box chart in Fig. 10. Group A typology buildings correspond to low-rise 1 BHK blocks, with built area equal to or less than 70 sq.m, Group B typology buildings correspond to low-rise 2 BHK blocks, with built area of 70–90 sq.m, and Group C typology buildings refer to 3-BHK individ-

Table 4
PV System Summary for Group A.

	Case 1 (a) Only Roof- 10.6 kWP	Case 2 (a) Façade + Roof- 17.6 kWp
Produced Energy	15.3 MWh/year	24.3 MWh/year
Specific Production	1449 kWh/kWp/year	1383 kWh/kWp/year
Performance Ratio	83.8 %	80.2 %
Normalized Production	3.97 kWh/kWp/day	3.79 kWh/kWp/day
Array losses	0.68 kWh/kWp/day	0.80 kWh/kWp/day
System Losses	0.09 kWh/kWp/day	0.14 kWh/kWp/day

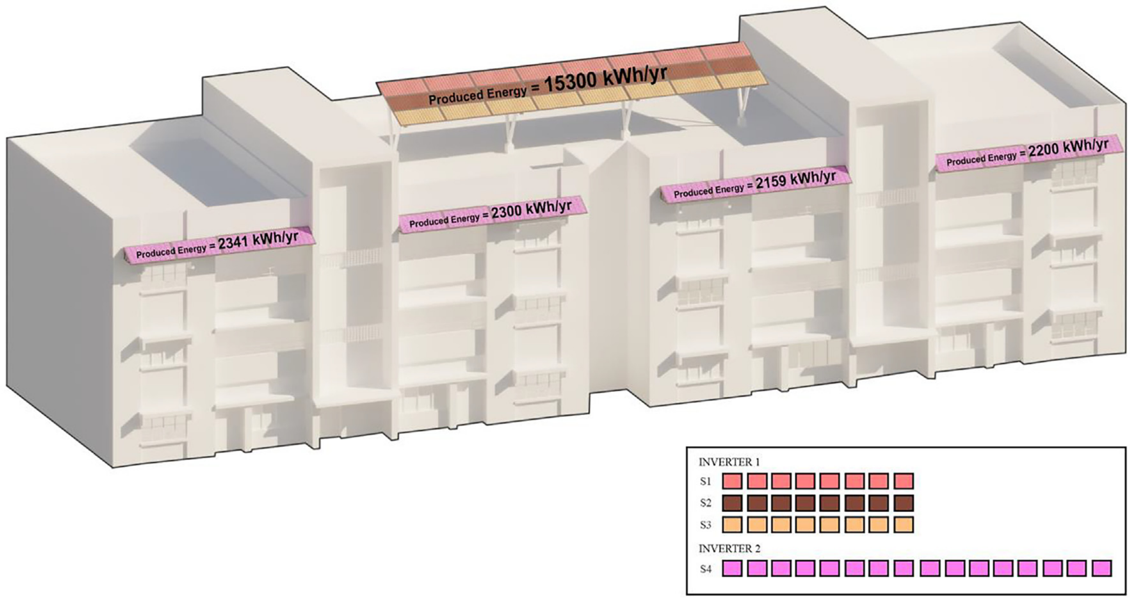


Fig. 11. 17.6 kWP rooftop and facade Solar BIPV System designed for Group A.

ual bungalows with area between 90-180 sq.m. It is seen that the electricity consumption pattern of the three identified groups is synonymous with the built area characteristics of the building. The group with the lowest built area (Group A) sees low electricity consumption up-to 3725 kWh/household/year, while the group with the highest built area (Group C) sees high electricity consumption up-to 13.83 MWh/household/year (recorded as outlier in box chart). This is attributed to not just the built area, but also the varying socio-economic and psychological parameters of the occupancy type in households of different typologies.

3.2. Simulation results

3.2.1. PV system design for Group A

Table 4 shows the summary of the simulated energy prediction of the PV system designed for both Case 1(a) and Case 2(a). The maximum demand of one block (12 units) of Group A is 22.78 MWh annually. In Case 1(a), the Roof PV produced energy from the 10.6 kWp plant is 15.3 MWh/year. This does not meet the maximum demand of the Group A. Thus, an additional façade integrated building photovoltaic of 7 kWp (total 17.6 kWp) is designed in addition to the rooftop as Case 2(a) (Fig. 11), producing total energy of 24.3 MWh/year.

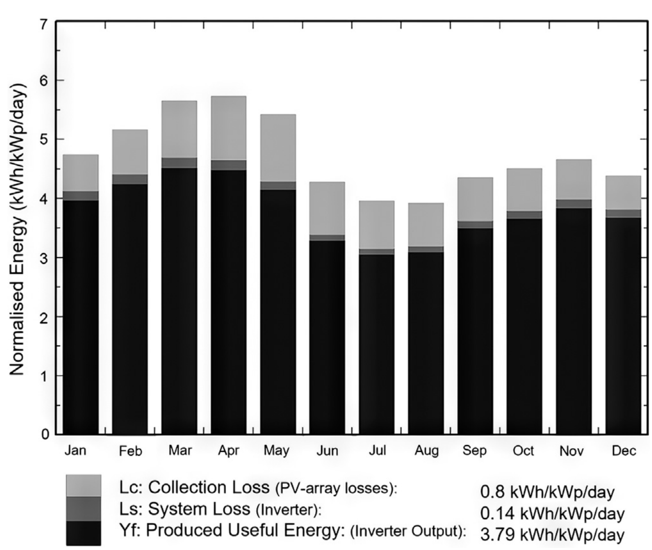


Fig. 12. Monthly Normalized production for integrated 17.64 kWp Plant for Group A.

Fig. 12 shows the normalized monthly production for the different months. The highest production can be seen in the month of March (4.70 kWh/kWp/day), and lowest in the month of July (3.16 kWh/kWp/day). The average normalized performance is 3.79 kWh/kWp/day with 80.2 % performance ratio throughout the year. The Collection losses amount to 0.8 kWh/kWp/day, the system losses are of 0.14 kWh/kWp/day, with an inverter output of 3.79 kWh/kWp/day.

The losses in the system depend on various factors such as the inverter and module technology, losses due to temperature and irradiance, ohmic wiring loss, shading loss (linear), various inverter and module array losses. The global horizontal irradiation is 1637 Kw/m^2 annually for Kharagpur. In Case 2(a), the effective irradiation on the collector plane is 1607 kWh/m^2. The solar energy incident on solar panel gets converted to electrical energy. The near shadings-irradiance loss is 3.7 %. The loss diagram generated by PVSyst shows that the efficiency of the PV array at STC is 22.02 % (Refer to Fig. A1 in Appendix A). The total energy available at inverter input over a year is 25.2 MWh. After the inverter losses the available energy obtained at the inverter output is 24.79 MWh. The final energy injected into the grid is 24.345 MWh after considering ohmic losses. The inverter output in this case is 80.2 %, with PV array loss of 16.9 % and system loss of 2.9 %. The total power generation of the 17.6 kWp is 24.3 MWh with a performance ratio of 0.80. Refer to Table A2 in Appendix A for main results and monthly balances for the proposed plant for Group A.

3.2.2. PV system design for Group B

The total maximum demand of one block of Group B is 24.3 MWh annually. In Case 1(b), the produced energy from the 10.6 kWp solar panel is 15.14 MWh/year. This does not meet the demand of the typology. Produced energy reaches 24.6 MWh/year

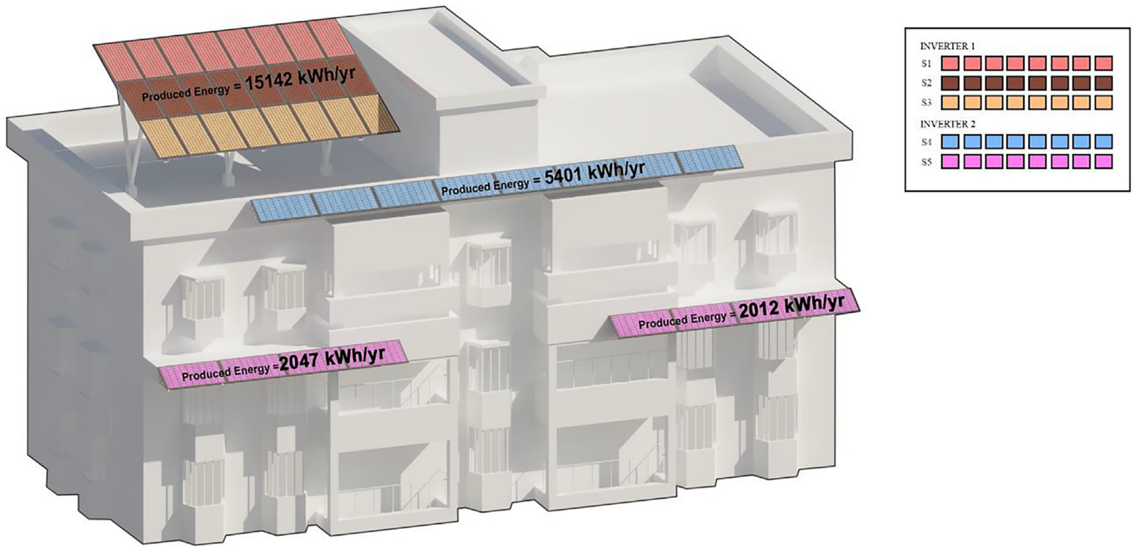


Fig. 13. Integrated 17.64 kWp rooftop and façade BIPV system for Group B.

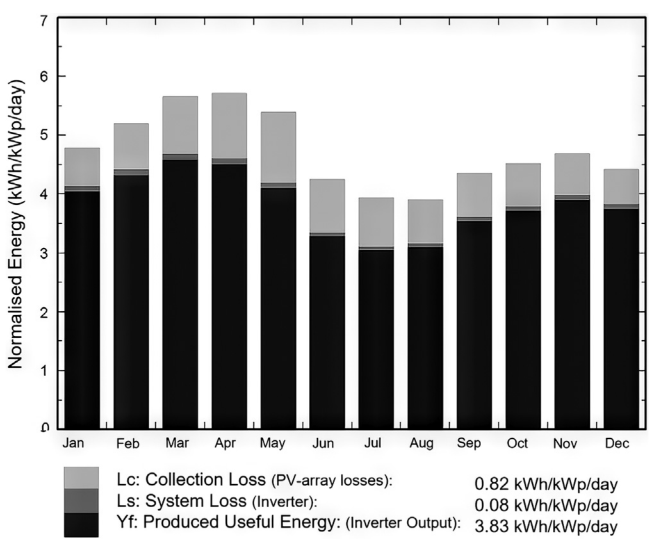


Fig. 14. Monthly Normalized production for integrated 17.64 kWp Plant for Group B.

Table 5G
PV System Summary for Group B.

	Case 1 (b) Only Roof- 10.6 kWp	Case 2 (b) Façade + Roof 17.64 kWp
Produced Energy	15.14 MWh/year	24.6 MWh/year
Specific Production	1434 kWh/kWp/year	1397 kWh/kWp/year
Performance Ratio	82.9 %	81.0 %
Normalized Production	3.93 kWh/kWp/day	3.83 kWh/kWp/day
Array losses	0.72 kWh/kWp/day	0.82 kWh/kWp/day
System Losses	0.09 kWh/kWp/day	0.08 kWh/kWp/day

for the 17.64 kWp plant (Fig. 13) comprising of a 7.04 kWP façade PV (Table 5).

Fig. 14 shows the monthly normalized production across various months for the integrated rooftop and Solar BIPV designed for Group B. The highest production is in the months of March (4.69 kWh/kWp/day), and least observed are in the months of July (3.12 kWh/kWp/day), after accounting for collection and system losses.

According to the report generated by PVSyst the efficiency of the system at STC is 22.02 %. The simulation reports 17.3 % array loss, 1.7 % system loss and 81 % inverter output (Refer to Fig. A2

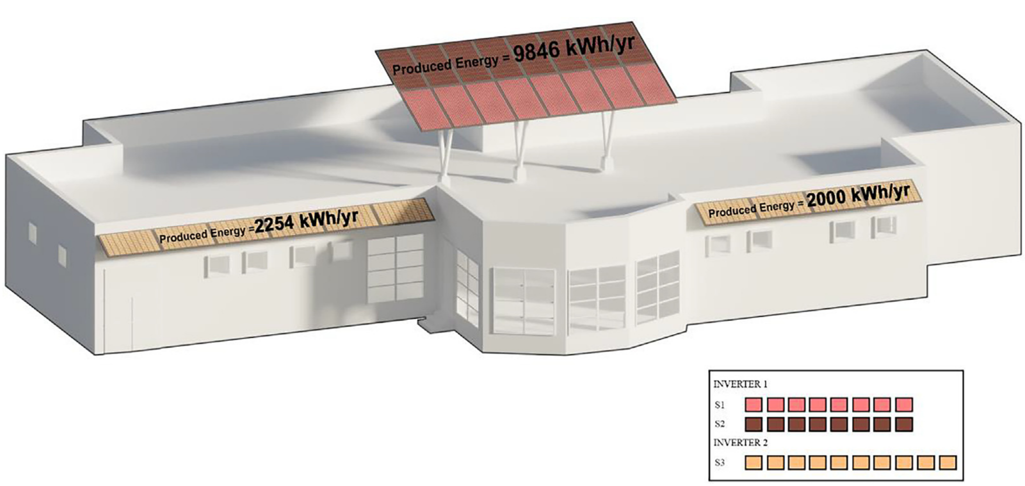


Fig. 15. Integrated 11.4 kWp PV system for Group C.

Table 6
PV System Summary for Group C.

	Case 1 (c) Only Roof- 7.0 kWp	Case 2 (c) Façade + Roof 11.4 kWp
Produced Energy	9,846 MWh/year	14.1 MWh/year
Specific Production	1399 kWh/kWp/year	1232 kWh/kWp/year
Performance Ratio	80.9 %	71.4 %
Normalized Production	3.83 kWh/kWp/day	3.38 kWh/kWp/day
Array losses	0.74 kWh/kWp/day	1.27 kWh/kWp/day
System Losses	0.17 kWh/kWp/day	0.08 kWh/kWp/day

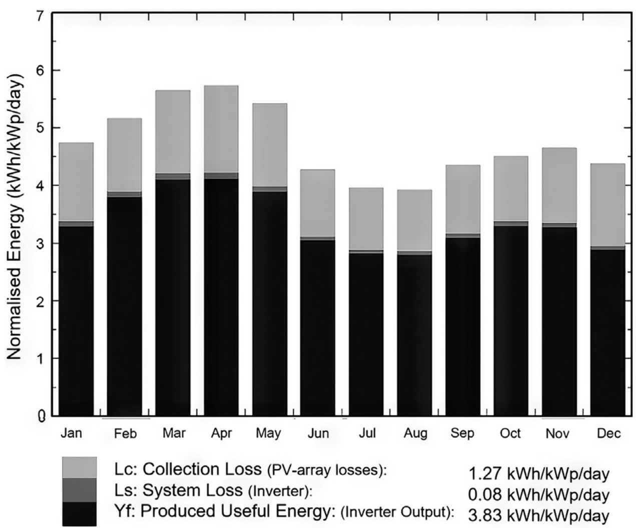


Fig. 16. Monthly Normalized production for integrated 11.4 kWp plant for Group C.

in Appendix A). The available energy at inverter output is of the 17.64 kWp is 24.8 MWh/year. After AC ohmic losses of 1 %, the system injects 24.6 MWh/year into the grid with a performance ratio of 0.81. Thus, the integrated façade and roof solar PV system meets the maximum requirement of a block of Group B, while maintaining a good performance ratio. Refer to Table A3 in Appendix A for main results and monthly balances for the proposed plant.

3.2.3. PV system design for Group C

The total maximum demand of one block of Group C is 13.83 MWh annually. The rooftop 7.04 kWp plant produces energy equivalent to 9.84 MWh/year. This does not meet the demand of typology C. The 11.4 kWp integrated plant (Fig. 15) with the additional 4.4 kW façade integrated building photovoltaic, produces 14.1 MWh/year energy as seen in Table 6. The 11.4 kWp plant meets the demand of Group C by 100 %.

Fig. 16 shows the monthly normalized production for the integrated rooftop and facade11.4 kWp plant. It can be seen that the highest production is in the months of April (4.23 kWh/kWp/day), and least observed are in the month of August (2.87 kWh/kWp/day), after accounting for collection and system losses.

According to the loss diagram generated by PVSyst for the integrated solar PV for Typology C, array losses for Case 2(c) is 26.9 %, with 1.6 % system loss, thus we get a 71.4 % inverter output (Refer to Fig. A3 in Appendix A). The efficiency at STC is 22.02 %, with Array nominal energy at 16.2 MWh. The energy injected into the grid is 14.1 MWh annually after accounting for 1.1 % AC ohmic loss. The total power generation of the 9.23 kWp is 14.15 MWh with a performance ratio of 0.78. Refer to Table A4 in Appendix A for main results and monthly balances.

3.3. Green house gas emission reduction from the proposed BIPV

The PV system lifetime has been considered for 30 years, with an annual degradation of 1 %. In Group A, for the 17.6 kWp plant, the total CO_2 emissions saved over lifetime is 566.7 tons, in Group

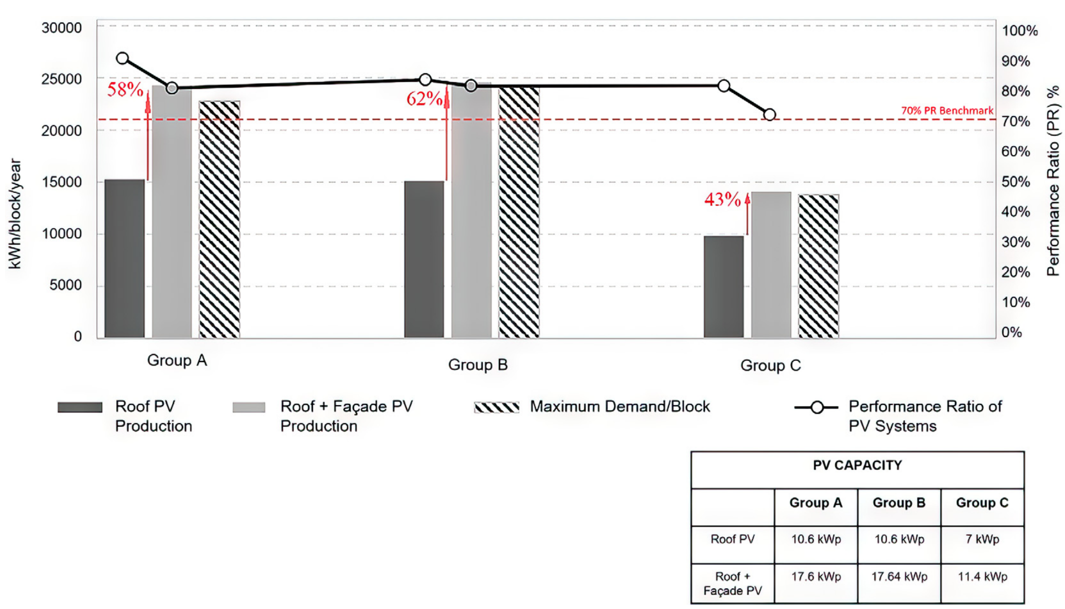


Fig. 17. Comparison of Produced Energy of PV Systems vs maximum demand of each block.

Table 7
Summary of Proposed Integrated Rooftop and Façade Solar PV System.

Building Typology	No.	Maximum Energy Demand (x)		Measured Energy Demand (x')		Nominal PV Sizing		Energy Produced by PV (y)		Surplus Energy (y-x')	Additional households catered by surplus	CO_2 emissions saved (Over 30 years)	
Group A	1 unit	*1898.3 kWh/year/household*		*1,145 kWh/year/household*		*1.46 kWp/household*		*2,028 kWh/year/household*			*370 additional households of Group A*	*47.2 tons/household*	
	1 block (12 unit) X40	*22,780 kWh/year/block*	***911.2 MWh/year for 40 blocks***	*13,750 kWh/year/block*	***550 MWh/year for 40 blocks***	*17.6 kWp/block*	***704 kWp for 40 blocks***	*24,346 kWh/year/block*	***973.8 MWh/year for 40 blocks***	***423.8 MWh/year***		*566.7 tons/block*	***22,668 tons for 40 blocks***
Group B	1 Unit	*4050 kWh/year/household*		*2,666 kWh/year/household*		*2.94 kWp/household*		*4100 kWh/year/household*			*96 additional households of Group B*	*87.7 tons/household*	
	1 block (6 unit) X30	*24,300 kWh/year/block*	***729 MWh/year for 30 blocks***	*16,000 kWh/year/block*	***480 MWh/year for 30 blocks***	*17.64 kWp/block*	***529 kWp for 30 blocks***	*24,600 kWh/year/block*	***738 MWh/year for 30 blocks***	***258 MWh/year***		*562.6 tons/block*	***15,798 tons for 30 blocks***
Group C	1 Unit X388	*13,830 kWh/year/household*	***5366 MWh/year for 388 units***	*7,216 kWh/year/household*	***2800 MWh/year for 388 units***	*11.4 kWp/household*	***4,423 kWp for 388 blocks***	*14,100 kWh/year/household*	***5,470.8 MWh/year for 388 blocks***	***2,670.8 MWh/year***	*370 additional households of Group C*	*308.5 tons/household*	***1,19,698 tons for 388 blocks***
Total (for all residential blocks in Campus)		***7,006.2 MWh***		***3,830 MWh/year***		***5.6 MWp***		**7182 MWh/year**		***3,352 MWh/year***		**1,58,164 tons**	

B for the 19.4 kWp plant, 562.6 tons of CO_2 emissions is saved , and in Group C for the 11.4 kWp plant, 308.5 tons of CO_2 emissions are evaded over the complete lifetime of 30 years.

3.4. Proposed system for grid-connected integrated roof and façade BIPV for achieving Net-Zero potential of residential units

The integrated façade and rooftop solar PV system is able to satisfy the maximum energy demand for each typology with adequate performance ratio, and is thus, considered for the proposed plant. Fig. 17 shows the comparison of the two proposed systems for each typology. The proposed additional 7kWp façade BIPV, improves the performance of the 10.6 kWp rooftop PV by 58.8 % for Group A, and 62.5 % for Group B. The 4.4 kWp façade BIPV installed for Group C, improves the performance of the 7.0 kWp rooftop PV plant by 43.2 %. The performance ratio is maintained at 71 % – 81 % for the façade integrated PV systems for all the three cases.

Table 7 shows the summary of the integrated Roof and Façade solar PV Plants extrapolated for all the residential units on campus. For Group A – 1 BHK low-rise apartment type, each block consisting of 12 houses have been provided with a 17.6 kWp plant generating 24.3 MWh/year with a PR of 80.2 %. A 17.6 kWp plant is designed for Group B – 2 BHK low-rise apartment type, containing 6 houses in 1 block, generating 24.6 MWh/year with a PR of 81 %. For Group C representing 3–4 BHK single storey bungalow, a 11.4 kWp plant has been proposed, that can generate 14.1 MWh/year with a PR of 71 %. The total nominal PV power of the proposed grid-connected plant for all residential units is 5.6 MWp, with an annual energy production of 7182 MWh. Additionally, a total of 1,58,164 metric tons of CO2 can be saved over the lifetime of 30 years by installing the Solar PV plant in all identified residential complexes. Moreover, it should be noted, that for Group A, a PV plant of nominal power 1.46 kWp/household can yield 2,028 kWh/year, adequate for meeting the maximum household consumption in 1BHK typology. A PV plant of capacity 2.94 kWp/household yields 4100 kWh required to meet the maximum demand of Group B household, and a PV plant of capacity 11.4 kWp/household producing 14,100 kWh/year is required to meet the maximum recorded demand of Group C household. As the PV system has been designed to meet the maximum energy demand of households in each typology, there is a surplus energy generation of 3,352 MWh/year when compared against the annual measured residential energy demand, that can cater to additional households as computed in Table 7.

It is also noted in the study, that although the energy produced by the proposed PV plant meets the total demand of each typology, there is inconsistency in month-wise energy production. The solar energy production in the months of June to September remain low due to reduced solar irradiation during peak monsoon climate, whereas the subsequent energy consumption in these months is highest annually owing to the use of cooling equipment to combat the high humidity and temperature in this period. The energy produced by the PV is 44 %-49 % more than the maximum demand in the first quarter, while the plant falls behind by up to 67 % of the maximum demand in the third quartile in the months of July to September (Refer to Fig. A4 in Appendix A).

3.5. Net- ZEB evaluation for the proposed PV system

Table 8 showcases the maximum and average EPI for the studied typology groups in kWh/sq.m/year. The average and maximum EPI (expressed in kWh/sq.m/year). of each typology has been evaluated based on the annual energy consumption and built area of the households in the dataset. Further, the Energy Generation Intensity (EGI) for each of the typology has been computed based on the energy production from the Solar PV system proposed for

Table 8
Residential energy benchmarking and Net-ZEB potential.

Residence Typology	Floor Area	Benchmarking Indices				Net-ZEB Potential (With existing FAR) REVISED *EPI*	
		EPI (kWh/sq.m/year) (Maximum demand)	*EPI'* (kWh/sq.m/year) (Average demand)	EGI (kWh/sq.m/year) (Roof + Façade)			
				Roof	Facade	Maximum demand *EPI*-EGI	Average Demand *EPI'*-EGI
Group A	50 sq.m	37.86 kWh/sq.m/year	22.9 kWh/sq.m/year	25.5 kWh/sq.m/year	15 kWh/sq.m/year	−2.64 kWh/sq.m/year	**−17.6 kWh/sq.m/year**
Group B	80 sq.m	50.6 kWh/sq.m/year	33.3 kWh/sq.m/year	31.5 kWh/sq.m/year	19.7 kWh/sq.m/year	−1.5 kWh/sq.m/year	**−17.9 kWh/sq.m/year**
Group C	170 sq.m	81.3 kWh/sq.m/year	42.4 kWh/sq.m/year	57.9 kWh/sq.m/year	25 kWh/sq.m/year	−1.6 kWh/sq.m/year	**−40.5 kWh/sq.m/year**

each Group in the current study (expressed in kWh/sq.m/year). The revised EPI has been formulated as a difference between the measured EPI and EGI. A negative value here showcases excess of energy generation over consumption, thus signifying surplus energy production of the specified systems. The Net-ZEB potential for the three groups of typologies can be observed from Table 8; with 17.6 kWh/sq.m/year, 17.9 kWh/sq.m/year, and 40.5 kWh/sq.m/year of surplus energy production when average measured EPI is considered, and 2.64 kWh/sq.m/year, 1.5 kWh/sq.m/year, and 1.6 kWh/sq.m/year of surplus energy production when maximum measured EPI is considered for Group A, B, and C households respectively.

4. Future research and limitation of study

Currently there is limited literature available on residential benchmarking based on housing typology for India. The energy performance index (*EPI*) calculated in kWh/sq.m/year is currently classified based on climatic zones for all housing typologies, and thus may disregard diversity in user behaviour and profile in different housing structures. Bureau of Energy Efficiency (BEE) has developed a residential building star rating plan based on Energy Performance Index that is climate specific for the five specified climatic zones by ECBC India [12]. Table 9 shows the residential star rating system developed by BEE for warm & humid climate. The average and maximum *EPI* for the three typology groups have been compared against the star rating provided by BEE. As West Bengal lies in Warm and Humid region, the measured average and maximum Energy Performance Index (*EPI*) of the studied housing groups can be rated the following based on BEE labels; 4–5 star rating for Group A, 2–3 star ratings for Group B, and less than 1-star rating for Group C type households. This may not paint a true picture, due to significant differences in built area, design and occupant profile of various typologies. It should thus be noted that the benchmark for residential units should not only be climate-specific, but also be defined for various typologies to create a specified benchmark for buildings in each of these groups. The findings of this study can be used to develop a novel framework for energy performance benchmarking and labelling system for residential building of varying scales in India [54].

Further, it is observed from the literature, that studies regarding energy efficiency in the built environment should be complemented with interventions to improve Indoor Air Quality (IAQ) to achieve holistic sustainability [53]. Thus, the following aspects can be explored for future work to further manage energy consumption of residential units in addition to solar PV installations:

- Study of Household Load Profile through monitoring electricity usage at household level using smart metering systems.
- Qualitative studies to evaluate occupancy, appliance usage and occupant-level energy consumption motives and trends through longitudinal and cross-sectional surveys across different household profiles in the study area.
- Evaluate aspects of Indoor Environmental Quality and its relation to Energy Consumption in different housing typologies.

Table 9
BEE Residential Star Rating for Warm and Humid Climate [12].

BEE Residential Star Rating Plan for Warm & Humid Climate	
1 Star	$58 < EPI \leq 64$
2 Star	$49 < EPI \leq 58$
3 Star	$39 < EPI \leq 49$
4 Star	$30 < EPI \leq 39$
5Star	$EPI \leq 30$

Previous studies have also explored the integration of green roofs with photovolatic panels [55], this can be explored for residential buildings. Additionally, the proposed grid-connected PV System has not taken into account battery storage, and thus may cause instability in power generation system during unfavourable solar conditions and non-sun hours. The present study can also benefit from a performance analysis of the existing PV system installed in hostels and academic buildings of the university campus. Moreover, future studies should also include a more elaborate analysis to determine optimal tilt and orientation in case of façade photovoltaic, as well as seasonal tilt due to lack of sufficient literature on the same. A detailed economic analysis has not been included in the main study, however the authors have derived the instalment cost breakup, net earnings and payback period from secondary sources, given in Table A5 and Table A6 in Appendix A.

5. Conclusion

This research illustrates the design and assessment of a grid-connected, integrated rooftop and facade Solar BIPV system for residential units in an academic campus, carried out using PVSyst software. In summary, three groups have been identified based on the typology of houses- 1 BHK low rise apartment, 2BHK low-rise apartment, and 3–4 BHK bungalows. The Solar PV system has been designed to meet the maximum energy demand of each identified typology during the pandemic affected period. The following conclusions can be drawn from the study:

- In addition to the academic buildings and student hostels, the energy consumption of residential units in university campuses should be taken into account while designing 'green or sustainable' campus. The residential electricity consumption during CoVid affected years (2020) went up by 15 % when compared to pre-pandemic annual consumption (2019). Thus, while designing the PV system, the maximum demand of these years is taken into account.
- Simulation studies done for residential units should take operational and functional constraints of designing Solar PV systems. Additionally, losses including shading, ohmic, thermal etc. should be carefully considered in simulation studies to reduce the error between actual and predicted energy generation. The capture losses vary monthly (maximum in July to September) due to monthly climate, whereas the system losses remain constant through the year.
- Integration of façade Solar PV with rooftop PV has been considered for the study due to the unavailability of adequate rooftop space in residential units with operational terraces. For the presently designed PV system, the facade integrated PV, placed at an optimized tilt of 30° on the Southern facade, enhances the energy production of the rooftop solar PV by up-to 62.5 % while maintaining a performance ratio above 70 %.
- Designing a Solar PV plant for low-rise buildings and bungalows are especially challenging due to shadowing by contextual objects. However, it was found that there existed 388 units of single storeyed 3-BHK bungalows, with high energy consumption of up to 13,830 kWh/year in the campus. By conducting a meticulous site study, shadow analysis, optimization of tilt angle and orientation, and supplementing rooftop PV with façade integrated solar BIPV, the photovoltaic potential of such typology of buildings can also be tapped.
- The maximum energy injected into the grid by the plant is in the months of March-April, while the least is in the months of July-September. When compared to demand, the most deficit in the PV generation is found in the months of June to September. The performance of PV deteriorates in this period due to low irradiance level attributed to high cloud cover. Additionally, these months experience high RH levels (85–89 %) along with high temperature (28–31 °C), causing occupants to use energy intensive equipment to increase thermal comfort. Thus, there is a disparity created in the demand and supply in these months which should be considered while designing and operating solar PV systems.
- Through evaluation of the Energy Performance Index and Energy Generation Index (EGI) expressed as kWh/sq.m/year, it is found that the Net-ZEB potential of the studied buildings is achieved through integration of the proposed Solar BIPV Plant.

Data availability

The authors do not have permission to share data.

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.

Acknowledgements

The authors would like to thank Indian Institute of Technology (IIT) Kharagpur, India for providing the electricity consumption data for the residential units on campus and providing support through Sponsored Research and Industrial Consultancy (SRIC) grant No: IIT/SRIC/AR/MWS/2021-2022/057.

Appendix A

Figs. A1-A4 and Tables A1-A6.

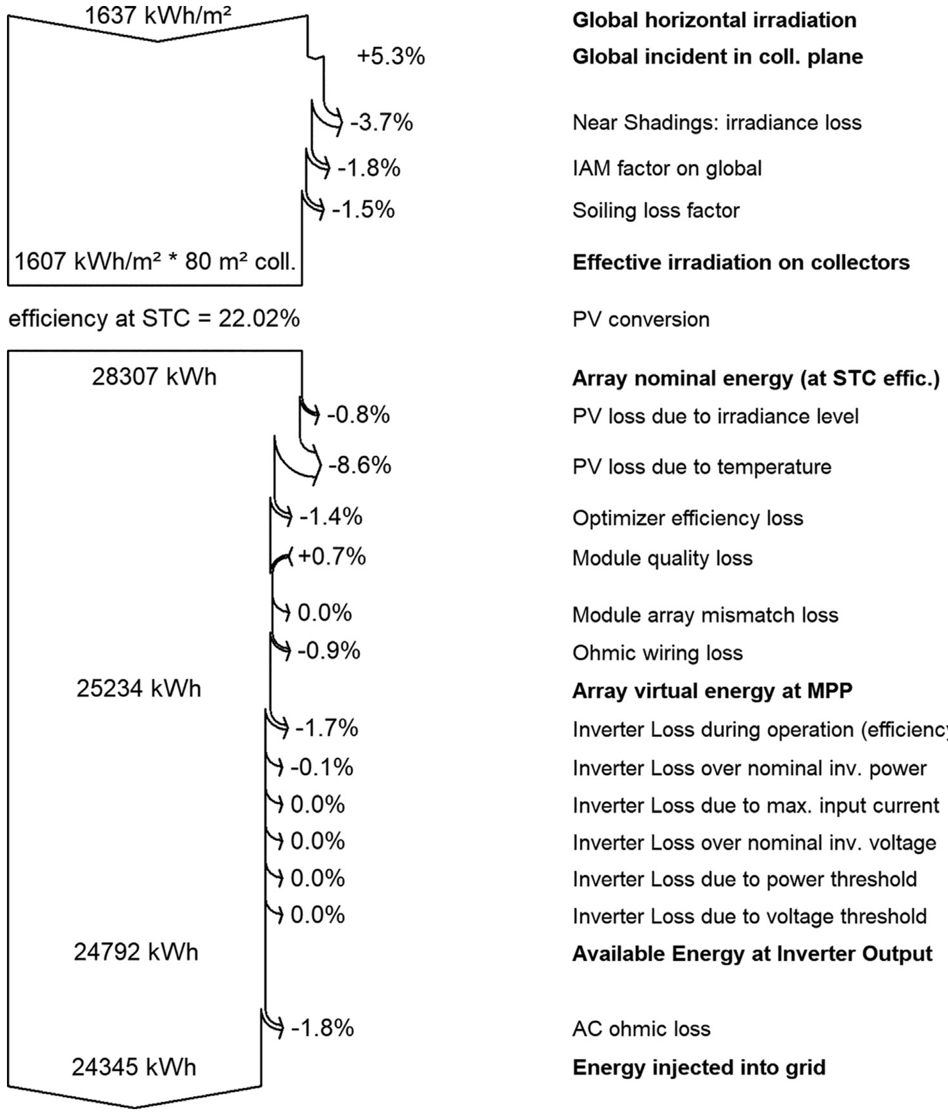


Fig. A1. Loss diagram generated from PVSyst for integrated 17.6 kWp Plant for Group A.

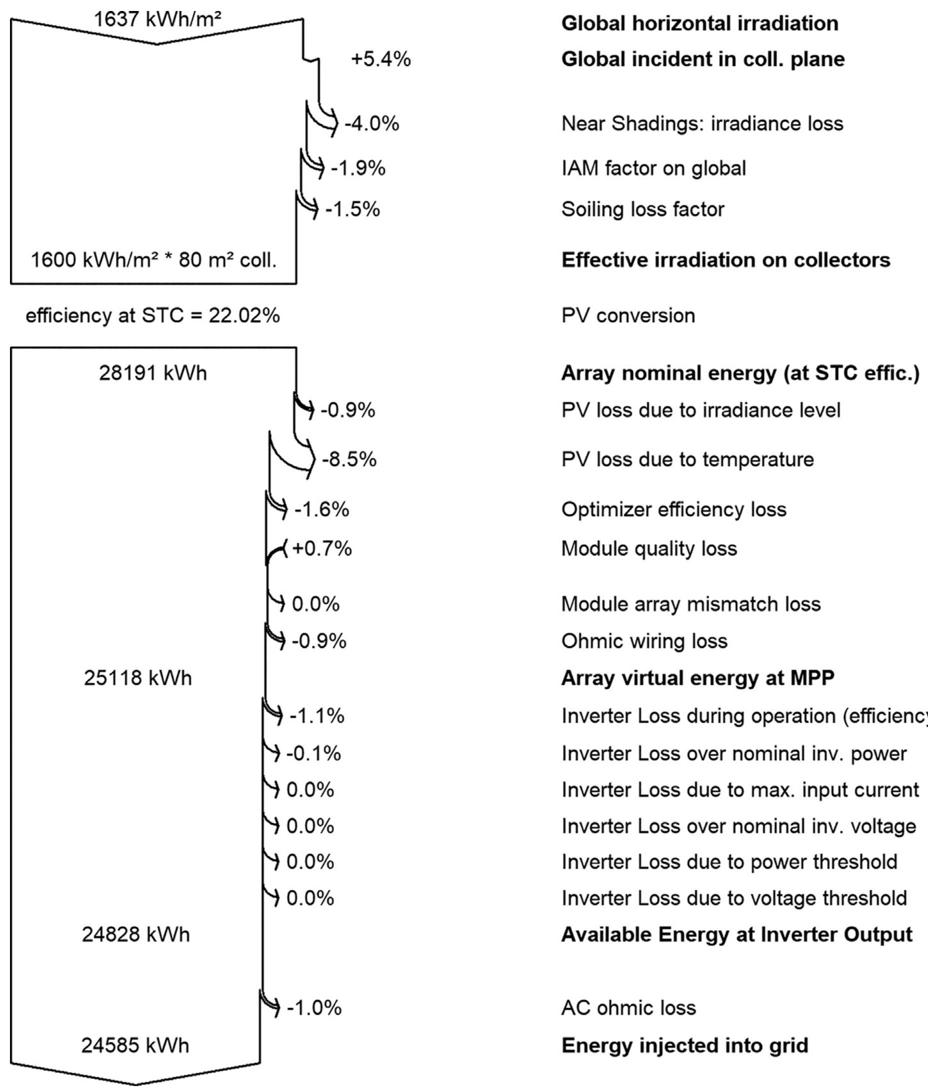


Fig. A2. Loss diagram generated from PVSyst for integrated 17.64 kWp Plant for Group B.

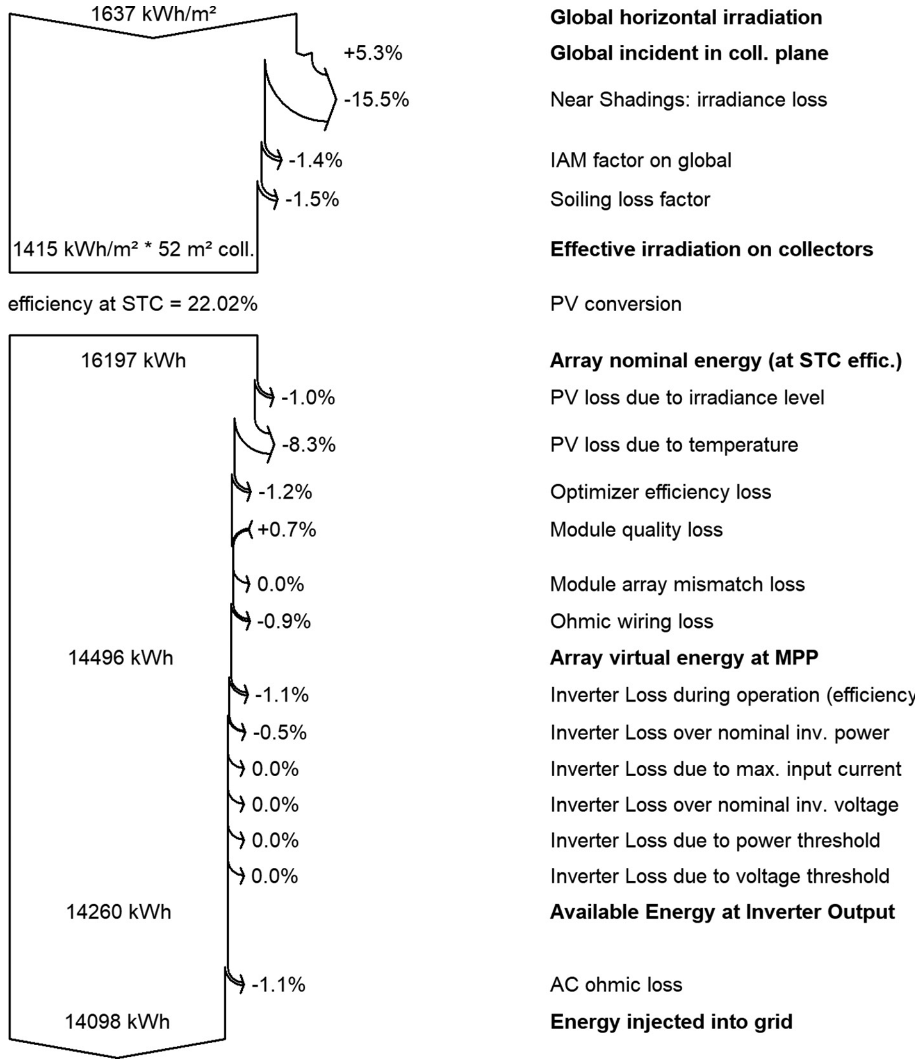


Fig. A3. Loss diagram generated from PVSyst for the integrated 11.4 kWp plant for Group C.

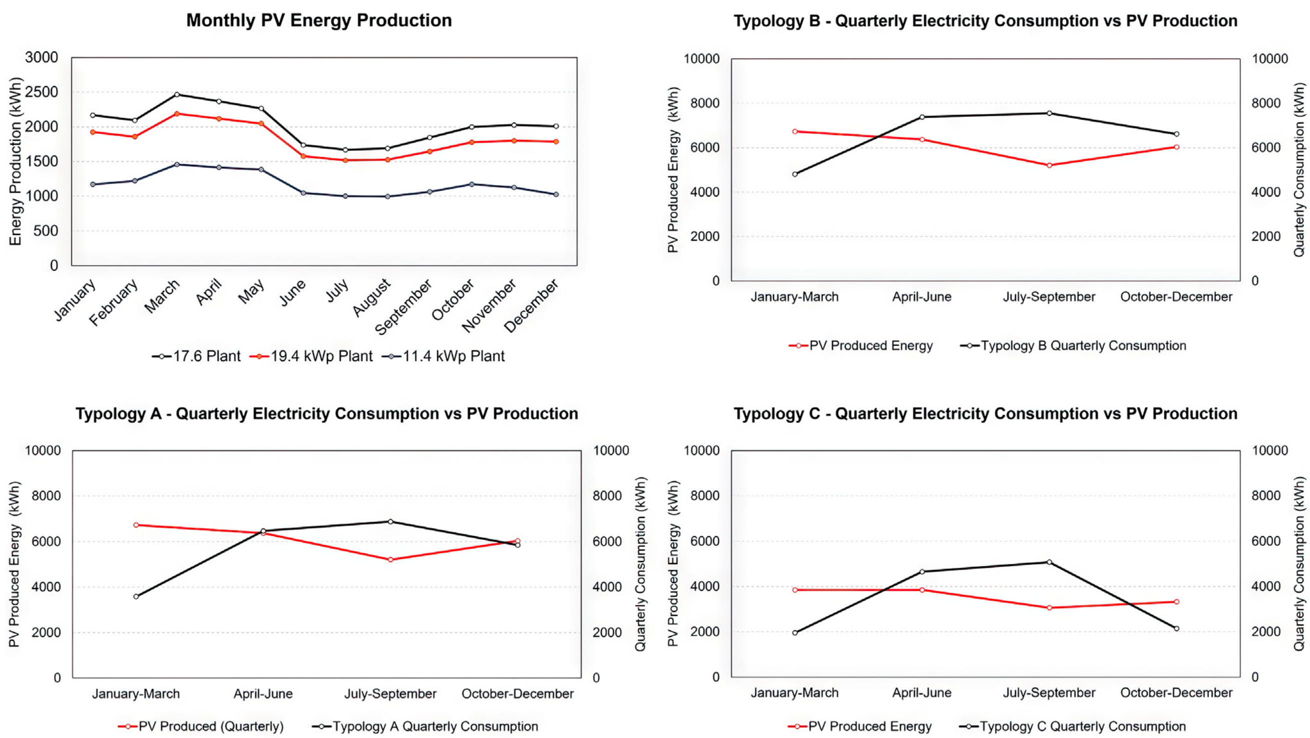


Fig. A4. Month-wise PV Energy Production for the three designed system.

Table A1
Performance assessment of Existing Solar PV plants through Measured vs Simulated outcomes.

Geographical Location	PV System Capacity/Type	Type of PV Technology	Software Used	Simulated Performance Outcomes	Measured Performance Outcomes	Reference
Kovilpatti, India	1.25 kWp/Wall, Façade, Roof	Poly-Crystalline	HOMER	South- 1050 kWh/year East-1198 kWh/year West-1150 kWh/year	PR: 84–87 % Production: 1791 kWh/year	[41]
Khatkar-Kalan, India	190 kWp	Poly-Crystalline	PVSyst	156.40 MWh/year	PR-74 % Production: 154.43 MWh/year	[58]
Andhra Pradesh, India	1 MW/Rooftop	Poly-Crystalline	PVSyst	1774 MWh/year	PR- 87.9 % Production: 1684.8 MWh/year	[46]
Telangana, India	10 MW/Ground mounted	Poly-Crystalline	PVSyst PV-GIS	16,047 MWh/year 16,403 MWh/year	PR- 85.12 % Production: 15,798.19 MWh/year	[21]
Malaysia	7.8 kWp/Rooftop	Poly-Crystalline	HOMER Pro	10,559 kWh/year	PR- 75.72 % Production: 10,740 MWh/year	[39]
Morocco	2 kWp/Rooftop	Mono-Crystalline Poly-Crystalline	PVSyst	236.6 kWh/month (February) 239.6 kWh/month (February)	PR ≈ 84 % (February), Error % in Production: (February) ≈4% PR ≈ 82 % (February)Error % in Production: (February) ≈4.5 %	[47]

Table A2
Main results and monthly balances for integrated roof top and façade 17.6 kWp Plant for Group A.

	GlobHor kWh/m2	DiffHor kWh/m2	T_Amb *C	GlobInc kWh/m2	GlobEff kWh/m2	EArray kWh	E_Grid kWh	PR Ratio
January	117.1	56.1	18.66	147	140	2253	2169	0.839
February	124.9	65.3	22.77	144.6	137.5	2174	2094	0.823
March	162.9	82	27.63	175.1	166.1	2562	2467	0.8
April	173.1	87.6	30.11	171.8	160.9	2458	2369	0.784
May	180.3	102.2	31.4	168	152.5	2343	2265	0.766
June	140.1	97.3	30.23	128.2	114.6	1792	1738	0.77
July	133.7	90	29.29	122.7	109.4	1721	1670	0.773
August	126.6	84.9	28.85	121.5	111.2	1746	1691	0.791
September	127.2	76.3	28.16	130.6	122.1	1912	1847	0.803
October	127.2	81.3	27.21	139.7	131.3	2069	1999	0.813
November	115.3	60.1	23.23	139.6	132.7	2103	2027	0.825
December	109	60	19.36	135.8	129	2084	2010	0.841
YEAR	1637.5	943.1	26.42	1724.7	1607.1	25,217	24,345	0.802

Table A3
Main results and monthly balances for integrated 17.64 kWp Plant for Group B.

	GlobHor kWh/m2	DiffHor kWh/m2	T_Amb *C	GlobInc kWh/m2	GlobEff kWh/m2	EArray kWh	E_Grid kWh	PR Ratio
January	117.1	56.1	18.66	148.1	140.7	2259	2212	0.848
February	124.9	65.3	22.77	145.3	138	2177	2131	0.833
March	162.9	82	27.63	175.3	166.2	2559	2504	0.812
April	173.1	87.6	30.11	171.3	159.3	2435	2383	0.79
May	180.3	102.2	31.4	167	148.6	2291	2244	0.763
June	140.1	97.3	30.23	127.4	112.9	1769	1735	0.774
July	133.7	90	29.29	121.9	107.9	1700	1667	0.777
August	126.6	84.9	28.85	121	109.9	1727	1693	0.795
September	127.2	76.3	28.16	130.5	122.2	1910	1872	0.815
October	127.2	81.3	27.21	140	131.8	2072	2030	0.824
November	115.3	60.1	23.23	140.5	133.3	2108	2064	0.834
December	109	60	19.36	136.8	129.8	2092	2050	0.851
YEAR	1637.5	943.1	26.42	1725.2	1600.5	25,099	24,585	0.81

Table A4
Main results and monthly balances for integrated 11.4 kWp plant for Group C.

	GlobHor kWh/m2	DiffHor kWh/m2	T_Amb *C	GlobInc kWh/m2	GlobEff kWh/m2	EArray kWh	E_Grid kWh	PR Ratio
January	117.1	56.1	18.66	146.8	114.1	1199	1172	0.698
February	124.9	65.3	22.77	144.8	122	1251	1222	0.739
March	162.9	82	27.63	175.1	150.1	1495	1459	0.729
April	173.1	87.6	30.11	171.9	146.4	1450	1416	0.72
May	180.3	102.2	31.4	168.2	141.5	1418	1386	0.72
June	140.1	97.3	30.23	128.4	105.1	1071	1049	0.714
July	133.7	90	29.29	122.9	99.9	1025	1003	0.714
August	126.6	84.9	28.85	121.6	99.9	1018	997	0.716
September	127.2	76.3	28.16	130.7	107.6	1090	1065	0.713
October	127.2	81.3	27.21	139.7	117.1	1200	1174	0.735
November	115.3	60.1	23.23	139.5	111.8	1152	1127	0.706
December	109	60	19.36	135.7	99.3	1050	1028	0.662
Year	1637.5	943.1	26.42	1724.9	1414.7	14,420	14,098	0.714

Table A5
Installation Cost Breakup of the proposed Solar PV System.

Proposed PV System Component	Group A – 17.6 kWp		Group B – 10.6 kWP		Group C	
	Price per Quantity	Total Price	Price per Quantity	Total Price	Price per Quantity	Total Price
Photovoltaic module – LG Electronics (440 W)	INR 22,000	8,80,000 for 40	INR 22,000	8,80,000 for 40	INR 22,000	INR 5,72,000 for 26
Solar Inverter – SolarEdge (8Kw/6Kw)	INR 10,000/kw	1,40,000 for 2 inverters	INR 10,000/kw	INR 1,60,000 for 2	INR 10,000/kw	INR 80,000 for 1
Solar Optimizer – SolarEdge	INR 3500/piece	1,40,000 for 40	INR 3500/piece	1,40,000 for 40	INR 3500/piece	INR 91,000 for 26
Mounting Structure	INR 32,000		INR 32,000		INR 15,000	
Wiring, ACDB, DCDB, Earthing Kit	INR 40,000		INR 40,000		INR 20,000	
Net monitoring device	INR 25,000		INR 25,000		INR 25,000	
Installation and Civil work	INR 50,000		INR 50,000		INR 25,000	
Government subsidy (for rooftop)	20 %		20 %		20 %	
Total Cost	**INR 10,45,600**		**INR 10,61,600**		**INR 6,62,400**	

Table A6
Net Earnings and Payback Period of the proposed Solar PV System.

Proposed PV System Component	Group A – 17.6 kWp		Group B – 21.1 kWp		Group C – 11.4 kWp	
	Energy Demand	Energy Generated by PV	Energy Demand	Energy Generated by PV	Energy Demand	Energy Generated by PV
	22,780 kWh/year	24,300 kWh/year	24,300 kWh/year	24,600 kWh/year	13,830 kWh/year	14,100 kWh/year
Tariff/kWh	INR 9.17/kWh		INR 9.17/kWh		INR 9.17/kWh	
Net Earnings/Cash Flow	INR 2,22,831		INR 2,25,582		INR 1,29,297	
Payback Period	**4.69 Years**		**4.7 Years**		**5.12 Years**	

References

[1] United States Energy Information Administration, IEO 2021 Narrative, 2021. www.eia.gov.

[2] M. Santamouris, K. Vasilakopoulou, Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation, E-Prime - Advances in Electrical Engineering, Electronics and Energy. 1 (2021), https://doi.org/10.1016/j.prime.2021.100002.

[3] R. Dalal, K. Bansal, S. Thapar, Bridging the energy gap of India's residential buildings by using rooftop solar PV systems for higher energy stars, Clean, Energy. 5 (2021) 423–432, https://doi.org/10.1093/ce/zkab017.

[4] Bureau of Energy Efficiency, Eco-Niwas Samhita 2021 – Part II: Electro-Mechanical and renewable Energy Systems, New Delhi, India, 2021. https://beeindia.gov.in/sites/default/files/ENS%202021.pdf (accessed October 18, 2022).

[5] Ministry of Statistics and Programme Implementation, Energy Statistics India 2022, India, 2022. https://mospi.gov.in/web/mospi/reports-publications/-/reports/view/templateFive/27201?q=RPCAT (accessed October 18, 2022).

[6] Ministry of Statistics and Programme implementation, Energy Statistics 2020, India, 2020.

[7] Bureau of Energy Efficiency, UNlocking NATional Energy-Efficiency potential (UNNATEE), 2017. https://beeindia.gov.in/sites/default/files/UNNATEE_0.pdf (accessed October 18, 2022).

[8] Government of India, Updated Nationally Determined Contribution of India, India, 2022. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1847812#:~:text=As%20per%20the%20updated%20NDC,based%20energy%20resources%20by%202030. (accessed October 18, 2022).

[9] Bureau of Energy Efficiency, Energy Conservation Building Code User Guide, New Delhi, India, 2009. https://beeindia.gov.in/sites/default/files/ECBC%20User%20Guide%20V-0.2%20%28Public%29.pdf (accessed October 18, 2022).

[10] Bureau of Energy Efficiency, Energy Conservation Building Code 2017, New Delhi, India, 2017. https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf (accessed October 18, 2022).

[11] Bureau of Energy Efficiency, Energy Conservation Building Code for Residential Building: Eco-Niwas Samhita- – Part 1 Building Envelope, India, 2018. https://www.econiwas.com/econiwascontrol/bower_components/ckeditor/kcfinder/upload/files/1.Workshop%20Presentation%201%20-%20Training%20Presentation_Training%20A_20.03.2020%20.pdf (accessed October 18, 2022).

[12] Bureau of Energy Efficiency, Energy Efficiency Labels for Residential Buildings, India, 2019. https://beeindia.gov.in/sites/default/files/Schedule%20-%20Residential%20building%20labelling.pdf (accessed October 18, 2022).

[13] W. Chung, Y.v. Hui, Y.M. Lam, Benchmarking the energy efficiency of commercial buildings, Appl Energy. 83 (2006) 1–14, https://doi.org/10.1016/j.apenergy.2004.11.003.

[14] F. Bano, V. Sehgal, A comparative study: Energy performance analysis of conventional office buildings at Lucknow, Journal of Design and Built, Environment. 20 (2020) 24–34, https://doi.org/10.22452/jdbe.vol20no1.3.

[15] Bureau of Energy Efficiency, Energy Benchmarks for Commercial Buildings, 2016.

[16] Prayas Energy Group, Centre for Policy Research, Trends In India's Residential Electricity Consumption, Plugging in : Electricty Consumption in Indian Homes : A Blog Series. (2017) 3. https://www.prayaspune.org/peg/trends-in-india-s-residential-electricity-consumption.

[17] T. Randazzo, E. de Cian, M.N. Mistry, Air conditioning and electricity expenditure: The role of climate in temperate countries, Econ Model. 90 (2020) 273–287, https://doi.org/10.1016/j.econmod.2020.05.001.

[18] E. Biyik, M. Araz, A. Hepbasli, M. Shahrestani, R. Yao, L. Shao, E. Essah, A.C. Oliveira, T. del Caño, E. Rico, J.L. Lechón, L. Andrade, A. Mendes, Y.B. Atlı, A key review of building integrated photovoltaic (BIPV) systems, Engineering Science and Technology, an, International Journal. 20 (2017) 833–858, https://doi.org/10.1016/j.jestch.2017.01.009.

[19] R. Goura, Analyzing the on-field performance of a 1-megawatt-grid-tied PV system in South India, International Journal of Sustainable Energy. 34 (2015) 1–9, https://doi.org/10.1080/14786451.2013.824880.

[20] M. Malvoni, A. Leggieri, G. Maggiotto, P.M. Congedo, M.G. de Giorgi, Long term performance, losses and efficiency analysis of a 960 kWP photovoltaic system in the Mediterranean climate, Energy Convers Manag. 145 (2017) 169–181, https://doi.org/10.1016/j.enconman.2017.04.075.

[21] K. Sudhakar, T. Srivastava, G. Satpathy, M. Premalatha, Modelling and estimation of photosynthetically active incident radiation based on global irradiance in Indian latitudes, International Journal of Energy and Environmental Engineering. 4 (2013) 21, https://doi.org/10.1186/2251-6832-4-21.

[22] R.M. Elavarasan, G.M. Shafiullah, N. Manoj Kumar, S. Padmanaban, A State-of-the-Art Review on the Drive of Renewables in Gujarat, State of India: Present Situation, Barriers and Future Initiatives, Energies (Basel) 13 (2020), https://doi.org/10.3390/en13010040.

[23] Ministry of New and Renewable Energy, Solar Energy, Https://Mnre.Gov.in/Solar/Current-Status/#:~:Text=The%20Mission's%20objective%20is%20to, Plants%20by%20the%20year%202022. (2022).

[24] B. Shiva Kumar, K. Sudhakar, Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India, Energy Reports. 1 (2015) 184–192, https://doi.org/10.1016/j.egyear.2015.10.001.

[25] S. Thotakura, S. Chandan Kondamudi, J.F. Xavier, M. Quanjin, G.R. Reddy, P. Gangwar, S.L. Davuluri, Operational performance of megawatt-scale grid integrated rooftop solar PV system in tropical wet and dry climates of India, Case Studies, Thermal Engineering. 18 (2020), https://doi.org/10.1016/j.csite.2020.100602.

[26] A. Alnoosani, M. Oreijah, M.W. Alhazmi, Y. Samkari, A. Alnoosani1, M. Oreijah2, M. Alhazmi3, Y. Samkari4, H. Faqeha5, Design of 100MW Solar PV on-Grid Connected Power Plant Using (PVsyst) in Umm Al-Qura University, Article in International Journal of Science and Research. (2019). 10.21275/30101901.

[27] K.S. Paller, J. Lomansoc, R.J. Roloma, Design and Simulation of 100 kWp Solar Photovoltaic (PV) Grid Connected Power Plant Using PVsyst, (2018). 10.13140/RG.2.2.22886.27209.

[28] S. Barua, R.A. Prasath, D. Boruah, Rooftop Solar Photovoltaic System Design and Assessment for the Academic Campus Using PVsyst Software, International Journal of Electronics and Electrical, Engineering. (2017) 76–83, https://doi.org/10.18178/ijeee.5.1.76-83.

[29] F.U.H. Faiz, R. Shakoor, A. Raheem, F. Umer, N. Rasheed, M. Farhan, Modeling and Analysis of 3 MW Solar Photovoltaic Plant Using PVSyst at Islamia University of Bahawalpur, Pakistan, International Journal of Photoenergy. 2021 (2021), https://doi.org/10.1155/2021/6673448.

[30] E. Tarigan, Djuwari, F.D. Kartikasari, Techno-economic Simulation of a Grid-connected PV System Design as Specifically Applied to Residential in Surabaya, Indonesia, in: Energy Procedia, Elsevier Ltd, 2015: pp. 90–99. 10.1016/j.egypro.2015.01.038.

[31] A. Aryal, N. Bhattarai, Modeling and Simulation of 115.2 kWp Grid-Connected Solar PV System using PVSYST, Kathford Journal of Engineering and Management. 1 (2018).

[32] N. Manoj Kumar, K. Sudhakar, M. Samykano, Techno-economic analysis of 1 MWp grid connected solar PV plant in Malaysia, International Journal of Ambient Energy. 40 (2019) 434–443, https://doi.org/10.1080/01430750.2017.1410226.

[33] C.P. Kandasamy, P. Prabu, K. Niruba, Solar potential assessment using PVSYST software, in: Proceedings of the 2013 International Conference on Green Computing, Communication and Conservation of Energy, ICGCE 2013, IEEE Computer Society, 2013: pp. 667–672. 10.1109/ICGCE.2013.6823519.

[34] P. Jagadale, S. Jadhav, P.R. Jagadale, A.B. Choudhari, S.S. Jadhav, Design and Simulation of Grid Connected Solar Si-Poly Photovoltaic Plant using PVsyst for Pune, India, 3 (2022) 41–49. 10.22044/rera.2021.11057.1069.

[35] N. Anang, S.N.A. Syd Nur Azman, W.M.W. Muda, A.N. Dagang, M.Z. Daud, Performance analysis of a grid-connected rooftop solar PV system in Kuala Terengganu, Malaysia, Energy Build. 248 (2021), https://doi.org/10.1016/j.enbuild.2021.111182.

[36] C. Dondariya, D. Porwal, A. Awasthi, A.K. Shukla, K. Sudhakar, M.M. Murali, A. Bhimte, Performance simulation of grid-connected rooftop solar PV system for small households: A case study of Ujjain, India, Energy Reports. 4 (2018) 546–553, https://doi.org/10.1016/j.egyear.2018.08.002.

[37] P. Ramanan, K. Kalidasa Murugavel, A. Karthick, K. Sudhakar, Performance evaluation of building-integrated photovoltaic systems for residential buildings in southern India, Building Services Engineering Research and Technology. 41 (2020) 492–506, https://doi.org/10.1177/0143624419881740.

[38] B. Parida, S. Iniyan, R. Goic, A review of solar photovoltaic technologies, Renewable and Sustainable Energy Reviews. 15 (2011) 1625–1636, https://doi.org/10.1016/j.rser.2010.11.032.

[39] C.E.C. Nogueira, J. Bedin, R.K. Niedzialkoski, S.N.M. de Souza, J.C.M. das Neves, Performance of monocrystalline and polycrystalline solar panels in a water pumping system in Brazil, Renewable and Sustainable Energy Reviews. 51 (2015) 1610–1616, https://doi.org/10.1016/j.rser.2015.07.082.

[40] N.S. Baghel, N. Chander, Performance comparison of mono and polycrystalline silicon solar photovoltaic modules under tropical wet and dry climatic conditions in east-central India, Clean, Energy. 6 (2022) 929–941, https://doi.org/10.1093/ce/zkac001.
[41] S. Sugianto, Comparative Analysis of Solar Cell Efficiency between Monocrystalline and Polycrystalline, INTEK: Jurnal Penelitian. 7 (2020) 92. 10.31963/intek.v7i2.2625.
[42] B. Navothna, S. Thotakura, Analysis on Large-Scale Solar PV Plant Energy Performance–Loss–Degradation in Coastal Climates of India, Front Energy Res. 10 (2022), https://doi.org/10.3389/fenrg.2022.857948.
[43] A. Allouhi, R. Saadani, T. Kousksou, R. Saidur, A. Jamil, M. Rahmoune, Grid-connected PV systems installed on institutional buildings: Technology comparison, energy analysis and economic performance, Energy Build. 130 (2016) 188–201, https://doi.org/10.1016/j.enbuild.2016.08.054.
[44] B. Ghaleb, M. Asif, Application of solar PV in commercial buildings: Utilizability of rooftops, Energy Build. 257 (2022), https://doi.org/10.1016/j.enbuild.2021.111774.
[45] K.O. Uwho, H.N. Amadi, Design And Simulation Of 500kw Grid Connected PV System for Faculty of Engineering, Rivers State University Using Pvsyst Software, 2022.
[46] I. Laib, A. Hamidat, M. Haddadi, N. Ramzan, A.G. Olabi, Study and simulation of the energy performances of a grid-connected PV system supplying a residential house in north of Algeria, Energy. 152 (2018) 445–454, https://doi.org/10.1016/j.energy.2018.03.157.
[47] S. Kumbar, A Review of Net Metering Mechanism and Its Process, Ipublisher. 12 (2016) 652–654.
[48] D.D. Milosavljević, T.S. Kevkić, S.J. Jovanović, Review and validation of photovoltaic solar simulation tools/software based on case study, 20 (2022) 431–451. doi:10.1515/phys-2022-0042.
[49] M. Lalwani, D.P. Kothari, M. Singh, Investigation of Solar Photovoltaic Simulation Softwares Knowledge Management View project Smart Grid View project Investigation of Solar Photovoltaic Simulation Softwares, INTERNATIONAL JOURNAL OF APPLIED ENGINEERING RESEARCH, DINDIGUL. 1 (2010). https://www.nrel.gov/a.
[50] S. Sinha, S.S. Chandel, Review of software tools for hybrid renewable energy systems, Renewable and Sustainable Energy Reviews. 32 (2014) 192–205, https://doi.org/10.1016/j.rser.2014.01.035.
[51] S. Labed, E. Lorenzo, The impact of solar radiation variability and data discrepancies on the design of PV systems, Renew, Energy. 29 (2004) 1007–1022, https://doi.org/10.1016/j.renene.2003.12.009.
[52] IEA, Development of CO2 emission intensity of electricity generation in selected countries, 2000-2020, 2020.
[53] A.N. Nair, P. Anand, A. George, N. Mondal, A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality, Environ Res. 213 (2022), https://doi.org/10.1016/j.envres.2022.113579.
[54] K. Panicker, P. Anand, A. George. Typology-wise Residential Energy Benchmarking and Net ZEB Potential: A Case Study of Residential Complexes inside IIT Kharagpur, India. In The 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (BuildSys '22), November 9–10, 2022 Boston, MA, USA. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3563357.3566142
[55] Gupta S, Anand P, Kakkar S, Sagar P, Dubey A. Effect of evapotranspiration on performance improvement of photovoltaic-green roof integrated system. Journal of Renewable Energy and Smart Grid Technology. 2017 Jun 21;12 (1):63-76.