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Research article

Integration of solar energy into low-cost housing for sustainable development: case study in developing countries

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ABSTRACT

The United Nations Development Program reported that two-thirds of the world's population will be living in cities by 2050, which would account for more than 60% of the world's energy consumption. Developing countries experience substantial urbanization and informal settlements compared with other parts of the world. This indicates a paradigm shift in the global energy landscape, which heralds an increase in greenhouse gas emissions. According to Indonesia's National Energy General Plan (PR 22), solar panels are expected to cover at least 25% of rooftops. In Uganda, the Sustainable Energy for All (SE4All) program aims to ensure high penetration of solar energy in the country. This study aims to integrate clean energy into low-cost housing development for sustainable cities in Uganda and Indonesia. We propose an optimal energy system and examine the most significant design parameters that exhibit a desirable performance ratio and energy yield. This project was undertaken in two stages: energy yield estimation and detailed energy system design using two different software programs. Stage 1 aimed to estimate the energy yield based on the available roof area considering existing homes in Uganda and Indonesia. A photovoltaic (PV) array was designed with suitable inverters, tilt angles, and orientations. Stage 2 was intended to determine the optimal tilt angles. Five different PV systems were developed and tested using the optimal tilt angle determined earlier. Finally, an optimizer was integrated into the PV system to investigate potential improvements in the energy yield. The inclusion of an optimizer significantly increased the energy yield from 0.5% to 5.3%. For Uganda, the levelized cost of electricity (LCOE) with and without an optimizer ranged from \$0.25/kWh to \$0.36/kWh, whereas for Indonesia, the LCOE ranged from \$0.25/kWh to \$0.3/kWh. The amounts of carbon dioxide reduction were 173.894 t and 122.742 t in Indonesia and Uganda, respectively. The techno-economic outcome of this study serves as a reference model for other developing countries planning similar initiatives that can be replicated with local contextualization and assistive schemes.

1. Introduction

Since 1990, there has been an increase of 213 million inhabitants of informal settlements in the global population (UN-Habitat, 2013: 126–8). The world's urban population living in informal settlements is approximately 25%. According to UN-Habitat (2015), informal settlements are defined as inhabitants having no security of tenure on the land that they live on. Housing does not abide by the planning and building regulations that are placed in areas that are geographically and environmentally sensitive. Insufficient housing causes major repercussions ranging from economic stagnation to health problems. Low-cost housing can mitigate concerns such as poverty and insufficient housing by providing affordable options for the public and creating job opportunities. With the implementation of low-cost housing, global sustainability can be achieved across various dimensions, including environmental, economic, social, and cultural.

According to the Sustainable Development Goals report in 2019, based on the eleventh goal of sustainable cities and communities (UNSDG, 2019), the urban population living in slums has declined. From 2000 to 2014, the urban population living in slums decreased, which ranged from 28% to 20%. This trend was reversed when the urban population living in slums increased to 23.5% in 2018. The number of slum dwellers has exceeded 1 billion and is mostly in three regions: Eastern and South-Eastern Asia (370 million), sub-Saharan Africa (238 million), and Central and Southern Asia (227 million). By the year 2030, it is expected that a global population of 3 billion will require adequate

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and affordable housing. The causes of an increase in slum dwellers are rapid urbanization and population growth, resulting in the occupation of space for the construction of new affordable housing. Figure 1 shows the breakdown of the urban population living in slums or informal settlements in 2018. Figure 2 shows the number of urban populations living in slums in Brazil, China, India, Indonesia, Uganda, and Ethiopia.

This paper focuses on Uganda and Indonesia. According to Mr. Sam Mabala, Ministry of Land, Housing and Urban Development, Uganda, 60% of the urban population of 6.3 million live in slums and informal settlements. Uganda envisions cities without slums without eliminating the residents of the slums. Uganda's tactic to achieve this objective is to establish a national slum upgrading strategy. This strategy aims to avert further sprouting of slums and improve the current living standards of Uganda (IHA, 2018). With respect to achieving sustainable low-cost housing, solar energy has significant potential in Uganda. A study by Hashemi and Cruickshank indicated that Uganda has approximately 8 sun hours per day with a solar insolation of 5–6 kWh/m^2/day. There is a potential solar electricity capacity of 200 MW in Uganda (Hashemi and Cruickshank, 2015). In Indonesia, particularly in Jakarta, slums still exist and these places are typically called "kampung" by the locals. Poor immigrant communities and low-income families live in self-built settlements without legal ownership of the government's land. This is largely because of high construction material costs and the lack of housing policies and management to accommodate local economic and social demands. These communities form cultural and social networks based on financial affordability and circumstances (Alzamil, 2018).

According to Herbert, the demand for affordable housing in Uganda has increased significantly owing to the increase in the low-income population from 6.6 to 10 million in 2017 within 4–5 years. This resulted in an increase in the cost of construction materials, such as cement and concrete. Research has been conducted to investigate the feasibility of adopting bamboo and compressed stabilized earth blocks (CSEBs) to replace high-cost construction materials such as burned bricks. These local indigenous materials are expected to replace conventional materials in different stages (Nuwagaba, 2020). Mukiibi mentioned several factors that inhibited low-income Ugandans from owning a decent house, including a lack of affordable building materials, land tenure security, and building regulations. Some indigenous materials, such as thatch, mud, wattle, and sun-dried bricks, are not recognized by the local authorities because of the low quality of construction and regularization. The majority of the construction material is still dependent on imported contemporary resources with high transportation costs. Other local materials, such as timber, thatch, papyrus, and local bricks, are considered substitutes. However, modern technology and regulations for quality control must be explored for sustainable development (Mukiibi, 2015). In Uganda, housing prices vary from USD 9000 to 719,000 owing to high land costs, construction materials, and infrastructure. Land costs contribute up to 25% of housing costs. Affordable housing provided by the government is 3.5 times cheaper than that by private-sector developers. Thus, the integration of solar photovoltaics (PVs) into housing can be subsidized by the government. The Uganda government aimed to increase the renewable energy share to 61% by 2017 and electricity access to 22% by 2022 (Hashemi and Cruickshank, 2015).

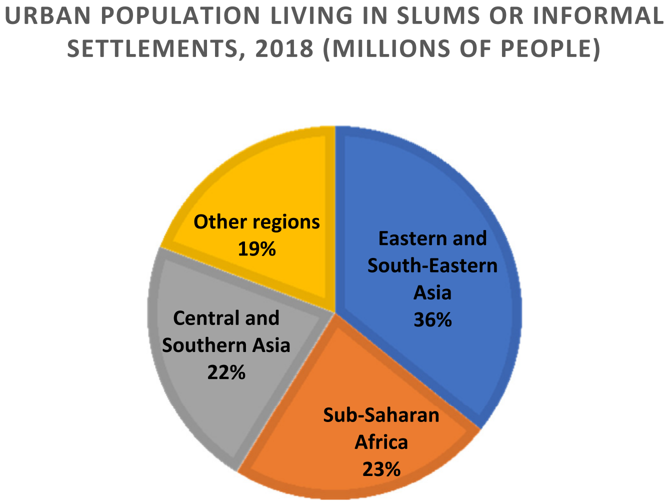

Figure 1. Urban population living in slums or informal settlements, 2018 (millions of people) (UNSDG, 2019).

Larasati mentioned that bamboo has been used as a building material in Indonesia for many years. Several governmental plans to promote the adoption of bamboo have been implemented. Bamboo is used as a building material to substitute wood to reduce the use of large amounts of tropical hard- and softwood as the main building materials that resulted in the tropical forest crisis. It can be considered a sustainable local building material for local cost housing (Larasati, 2007). Another study by Larasati, for Indonesia's scenario, indicated that local materials such as coconut fiber can be used as heat insulators on rooftops and cooling mechanisms for concrete floors. The adoption of local materials is expected to reduce the dependence on synthetic materials and time of transporting building materials. More alternative materials, suitable for wet tropical areas, can be explored via ecological building materials (Larasati, 2007). Research on the Indonesian real estate industry was not easily accessed. Housing prices have been increasing uncontrollably owing to a lack of government policies and market control. Thus, it is challenging to predict the price that is controlled by real estate developers. House pricing varies from one real estate developer to another, which is relatively subjective. In a study conducted by Rahadi et al., one of the corresponding factors, namely the green concept, had a respective score of 0.593 in a survey, reflecting the acceptance of green technologies among consumers (Rahadi et al., 2015).

Many studies have been conducted on sustainable low-cost housing, and they have mostly focused on energy-efficient technologies ranging from glazed windows to efficient heating systems. Exploration of renewable energy has yet to attain its fullest potential, and this paper focuses on adopting solar energy into low-cost homes in Uganda and Indonesia. The inclusion of solar energy to generate electricity will significantly benefit households. The excess energy produced by solar PVs can be fed into the grid with net energy metering to generate income for the households. The gap addressed in this paper is the adoption of solar PVs into sustainable low-cost housing plans to provide clean energy for homes. In countries such as Uganda and Indonesia, there is limited research on this topic. This study investigated the feasibility of integrating a solar PV system into low-cost housing in these two countries with a techno-economic assessment and recommendations for the optimal design. In Stage 1, resource assessment for selected locations in both countries was conducted. This was followed by the energy yield estimation stage to compute the monthly energy production and performance ratio. In Stage 3, a detailed energy system design was conducted to identify the precise energy production. Finally, economic and environmental analyses were performed for the optimized PV system in both locations.

2. Renewable energy in sustainable development

The severity of the population scenario in Uganda and Indonesia is shown in Figure 3. From 1990 to 2014, there was an increase in the urban population, resulting in many slum dwellers owing to rapid urbanization, which caused low-income citizens to move to cities in search of jobs. When citizens are unable to obtain employment, the number of people affected by poverty increases, causing the mushrooming of slums. In achieving sustainable low-cost housing in these countries, the implementation of renewable energy sources is a good strategy. Uganda and Indonesia are countries with long sun hours of approximately 8 and 12 h, respectively. In 2020, the solar energy capacity in Indonesia was approximately 172 MW (Statista, 2021), and solar energy is expected to

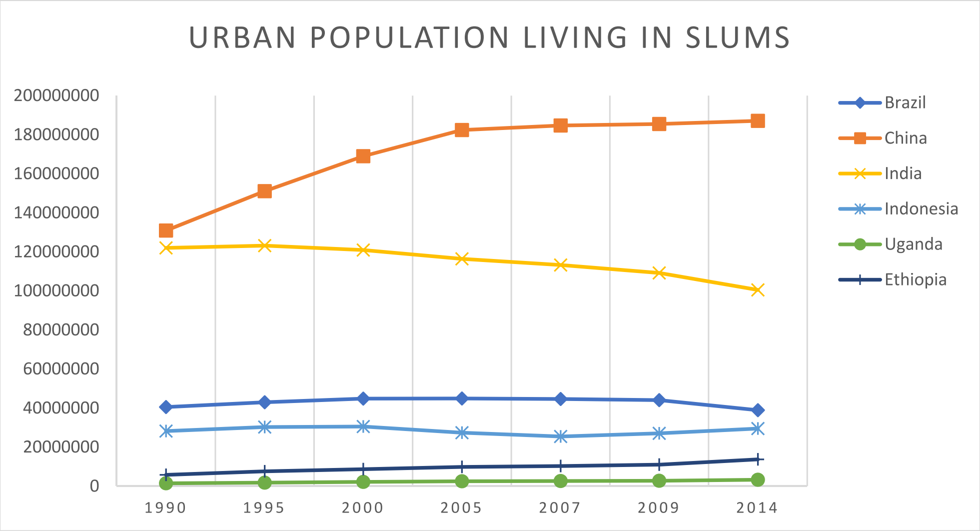

Figure 2. Urban population living in slums (Ritchie and Roser, 2018).

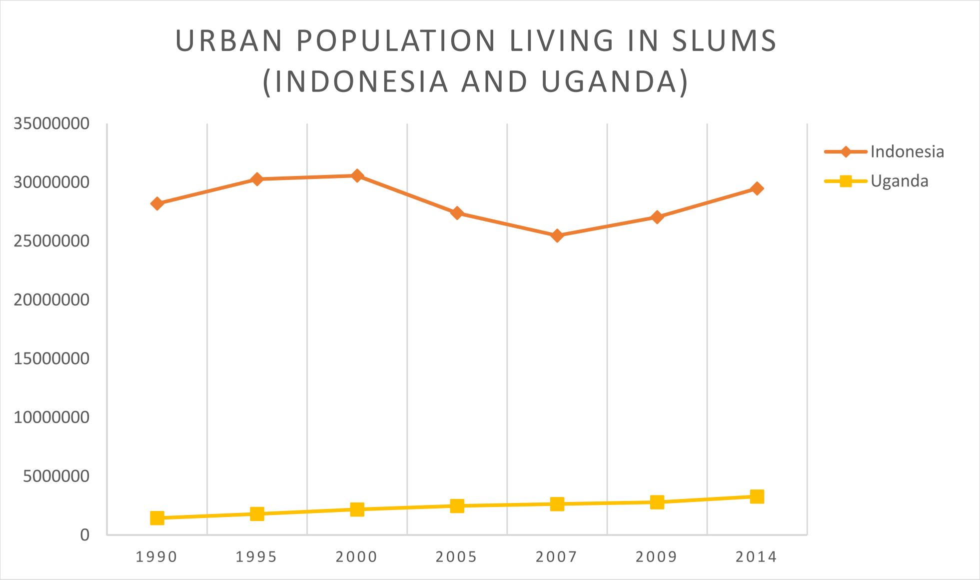

Figure 3. Urban population living in slums for Indonesia and Uganda (Ritchie and Roser, 2018).

contribute 5000 MW out of the anticipated total cumulative capacity of 41,700 MW by 2040 in Uganda (Aarakit et al., 2021).

Uganda created a policy for renewable energy in 2007, which aims to diversify the energy mix of the country. The primary concern of the country is the limited diversification among renewable energy technologies, which largely rely on hydro energy. In Uganda, the thermal process depends heavily on biomass, which is responsible for over 89.9% of the energy generated in the country (Heteu, 2015). In Indonesia, the use of renewables is rapidly increasing and is expected to include modern renewables (excluding traditional biomass) as much as 23% in the generation mix by 2025. The International Renewable Energy Agency (IRENA) indicated that solar energy has significant potential in Indonesia (IRENA, 2017). The Renewable Energy Roadmap (REMap) has identified that the generation of 47 GW of energy from installed PVs can be achieved by 2030. This is inclusive of 1.1 million homes in rural areas to be incorporated with solar PVs to provide electricity.

Sustainable development for low-income housing is associated with energy efficiency and adopting a low-carbon emission lifestyle. Green technology is closely related to sustainable development and can be defined as technologies that are subsumed into building designs to ensure that housing development has achieved a sustainable outcome. Green technologies include options that can save and generate energy or use energy efficiently (Darko et al., 2018). They can be divided into two stages: the design stage and the entire lifecycle. Several approaches can be implemented when discussing sustainable housing in the construction industry based on studies by researchers. Zhang et al. categorized green technologies into energy efficiency, indoor environmental quality enhancement, material efficiency, water efficiency, operations, and maintenance optimization (Zhang et al., 2011). Roufechaei et al. classified them based on the responsibility of the designer, i.e., architectural, mechanical, and electrical (Roufechaei et al., 2014). Sullivan and Ward identified four possible technology interventions that are suitable for low-income housing development: i) microclimate design and technologies to support greater energy efficiency; ii) renewable energy technologies to support access to alternative energy; iii) water and wastewater technologies to promote water conservation and quality; and iii) waste systems to promote resource reuse and recycling (Sullivan and Ward, 2012).

Probing renewable energy provides an opportunity for alternative sources of energy and can save conventional fuels that continue to be depleted. Solar energy is a source that can be conveniently integrated into residential sectors. Building-integrated photovoltaic (BIPV) systems are being developed rapidly as the technology continues to mature (Zhai et al., 2007). Tropical cities such as Kuala Lumpur exhibit significant potential for the deployment of BIPVs but have not yet fully ventured into this technology. The country receives a significant amount of solar irradiance throughout the year, and citizens have demonstrated a keen interest in adopting solar energy (Haw et al., 2009). To increase the demand for PV integration into the residential sector, James et al. suggested that the module cost, consumer interest, and suitable solar energy policy schemes should be considered. The incorporation of BIPVs into housing development is advantageous as a household can generate electricity instead of relying on the grid (Hachem et al., 2012). BIPVs also have a limitation, which is the possibility of downtime during winter or monsoon seasons; therefore, they may not be reliable (James et al., 2011). Willis et al. argued that the introduction of a feed-in-tariff (FiT) and a subsidy can promote the installation of BIPVs in homes as the payback period is not promising. Solar energy has significant potential as conventional fuels are not required, which is good for the environment (Willis et al., 2011). The locations of interest, Kampala in Uganda and Yogyakarta in Indonesia, have solar irradiances of 5.2 kWh/m^2 per day (Uganda – GET.invest, 2021; Aarakit et al., 2021) and 4 kWh/m^2 per day (NA, 2012), respectively; the solar irradiance is adequate and can therefore ensure a favorable response. Incorporating solar energy in the development of low-cost housing, as suggested by Pinto et al. for Brazil is a viable solution for generating electricity (Pinto et al., 2016). Table 1 and 2 presented related work and their key findings.

Hachem-Vermette et al. studied the energy performance of a solar mixed-use community. The study examined communities that integrated solar energy into commercial and residential buildings. The study was conducted in Calgary, Canada, which represents a northern cold climate. With the incorporation of PV systems into the neighborhood, the energy performance was measured based on the energy consumption and generation capabilities. The environmental impact of the integration and greenhouse gas emissions were considered. The study serves as a benchmark or guide for designing and analyzing energy-efficient mixed-use neighborhoods. The energy simulations demonstrated that attached and detached houses can achieve an energy positive status in the given climatic conditions. Apartment buildings, offices, and supermarkets can generate a smaller portion of the energy consumption of these buildings. This is because of the limited surface area of the roof for the installation of PV systems. In commercial buildings, energy demand surpasses energy generation (Hachem-Vermette et al., 2016).

Ouria and Sevinc studied the use of solar energy in urban areas, as exemplified by Famagusta in Cyprus. They considered climatic and geographic factors to analyze and compute the solar energy potential. The Duffie Beckman and Stephenson's cousin methods were used to analyze the energy yield, climatic and geographical factors, radiation, orientation, and landscape. The study concluded that Famagusta has potential for solar energy utilization, but its full potential cannot be achieved owing to poor urban design. The energy modeling tool used was Ladybug–Grasshopper in Rhino software. The model determined that the direct radiation is 695.03 Wh/m^2 and that the global horizontal radiation is 1121.75 Wh/m^2. Famagusta has a potential of 4383 sunlight hours, 76% of which is used, and the remaining is untapped because of bad weather such as cloudy, hazy, and foggy days (Ouria and Sevinc, 2018). Kodysh et al. identified a methodology suitable for estimating solar potential on multiple building rooftops. The methodology was developed to use light direction and raging (LiDAR) data and the geographic information system (GIS) to estimate the solar energy on individual buildings on a daily and monthly basis. As obtaining solar radiation data on individual housing is a challenge, they proposed a method of estimating solar radiation for multiple buildings in the city. The input parameters that influence the sun's radiation intensity on the earth's surface were

Table 1. Summary of related research - part 1.

Author	Title	Key Findings
Pinto et al. (2016)	Deployment of photovoltaics in Brazil: Scenarios, perspectives, and policies for low-income housing	• Electricity bills reduced significantly as solar panels supplied 83.5% of the demand during winter and autumn (worst case scenario). • Adopting 4 to 7 of 217 W PVs enabled 47% grid feedback for 30 years. • FiT will encourage dwellers to adopt BIPVs, but this is at the expense of the government.
Kazem et al. (2013)	Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman.	• Optimal tilt angle was obtained using an active sun tracker. • Optimal PV system has a sizing ratio of 1.33, whereas the sizing ratio for a battery is 1.6. Cost of energy generated by the proposed system is 0.196 USD/kWh. • Recommended changing the tilt angle twice a year. PV array should slant at 49° from 21st September to 21st March and placed horizontally ($\beta = 0^{\circ}$) from 21st March to 21st September.
Khatib et al. (2012)	Optimization of a PV/wind micro-grid for rural housing electrification using a hybrid iterative/genetic algorithm: case study of Kuala Terengganu, Malaysia.	• Model output energy of PV array based on daily solar energy, PV array area, PV module conversion efficiency, and DC–DC converter efficiency. • Optimization was conducted with loss of load probability (LLP). • Solar energy output recorded as 5.12 kWh/m^2 outperformed energy output from a wind turbine of 1.73 kWh/m^2.
Enteria et al. (2014)	Case analysis of utilizing alternative energy sources and technologies for the single-family detached house.	• Renewable energy was adopted to provide thermal and electrical energy to support main home systems (HVAC, electrical appliances, lighting systems). • Installed PV roof tiles supported 60%–80% of the electricity. • Solar energy collection exhibited 26% of primary thermal energy requirement of single detached houses.
Yang and Yu (2015)	Energy efficiency: green energy and technology.	• Energy-efficient technologies refer to technologies that reduce the energy consumption required to provide goods and services. • These technologies include energy-efficient lighting, window, HVAC system, household appliances, renewable energy systems, building orientation, and natural ventilation. • Energy efficiency technologies can be treated as alternative energy sources, equivalent to 2.2 billion tons of fuel, accounting for 20% of final energy consumption by 2030.
Roufechaei et al. (2014)	Energy-efficient design for sustainable housing development	• Carbon footprint of the housing industry is a major contributor to climate change, resource depletion, and pollution globally. • Energy efficiency parameters include insulation material,

(*continued on next page*)

Table 1 (*continued*)

Author	Title	Key Findings
		types of lighting, energy-saving appliances, passive solar system, natural ventilation, and clean electricity. • Energy-efficient options such as proper insulation and lighting are considered affordable solutions for housing.
Darko et al. (2018)	What are the green technologies for sustainable housing development? An empirical study in Ghana	• Natural ventilation, energy-efficient lighting systems, optimizing building orientation and configuration, energy-efficient HVAC systems, installation of water-efficient appliances are the five most important green technologies. • Adoption of natural ventilation is ranked as the priority in the housing industry in Accra, Ghana. • Water efficiency with a mean of 4.19 and energy efficiency technologies with a mean of 4.06 are ranked highest as criteria in sustainable housing development.
Lau et al. (2017)	Investigating solar energy potential in tropical urban environment: A case study of Dar es Salaam, Tanzania	• Numerical modeling of solar irradiance on building roofs and facades. Case studies at urban neighborhoods on the effect of urban morphology on energy yield. • Shading effect of high-rise buildings on the surrounding low-rise housing areas. • Most of the roofs received $\geq$1500 kWh/m^2 annually, which is sufficient for the electricity consumption of 100 kWh/y/capita for households.
Teo and Go (2021)	Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia.	• Optimized BIPV system for urban agriculture application. • Investigation of load demand and development of solar/hybrid/storage for a vertical farming system. • Design focused on energy yield and performance ratio supported by economics and environmental assessments. • Minimum and maximum energy consumptions are 430.116 and 1002.024 kWh, respectively. • Minimum and maximum solar system performance ratios are 82.22% and 82.56% respectively.

considered for this method: surface orientation, shadowing effect, elevation, and atmospheric conditions. The results from this method had a better estimation of solar radiation of individual buildings as the method considered the buildings' characteristics and possible shading (Kodysh et al., 2013).

Awad and Gül developed a systematic framework to simulate and optimize solar systems for shared communities. Two scenarios were simulated for a sustainable environment. The first scenario connected a small PV system to each unit. The second scenario was a large PV system connected to all units. The study indicated that the best option to facilitate a green residential housing system was to incorporate shared solar PV systems that are distributed evenly among the units. The study observed that when an individual solar PV system is connected to each unit, the household only uses 25% of the energy produced (Awad and

Table 2. Summary of related research - part 2.

Author	Title	Key Findings
Hachem-Vermette et al. (2016)	Energy performance of a solar mixed-use community	• Adopted EnergyPlus, ScketchUp plugin, and TRNSYS to estimate heating/cooling load, energy consumption, and building geometry data. • Houses with large roofs such as schools can achieve energy positive status for all scenarios. • Environmental performance is assessed in terms of primary energy use and GHG emissions. Results of schools and houses exhibited a net positive environmental impact annually.
Ouria and Sevinc (2018)	Evaluation of the potential of solar energy utilization in Famagusta, Cyprus	• Famagusta City has good potential for solar energy. However, the city is unable to harvest this resource optimally owing to inappropriate urban design. • Energy modeling was adopted for Famagusta City via Ladybug–Grasshopper in Rhino software. • Direct, diffused horizontal, and global horizontal radiations are 695.03, 426.72, and 1121.75 Wh/m^2, respectively.
Kodysh et al. (2013)	Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems	• Method combines high-resolution discrete element method data with upward-looking hemispherical viewshed algorithm. • Computation of unique variables that influence solar radiation potential for a particular building. • Rooftop solar radiation maps obtained using the proposed method provide better estimations of the solar radiation potential of individual buildings.
Awad and Gül (2018)	Optimization of community shared solar application in energy-efficient communities	• Community shared solar PV systems that are distributed evenly are effective in facilitating net-zero energy for the community. • Adopted generalized reduced gradient nonlinear optimization algorithm to design optimal PV sizing. Optimal tilt angle was observed at ± 3° of local latitude coupled with a southwest-facing azimuth angle. • Proposed framework is systematic and can be used to simulate individual households and communities of any size.
Alshammari and Asumadu (2020)	Optimum unit sizing of hybrid renewable energy system utilizing harmony search, Jaya, and particle swarm optimization algorithms	• Four hybrid systems were designed including solar PV, WT, biomass system, and battery bank. Optimum system to fulfill the electrical requirements of small rural communities was determined. • Two optimization algorithms were used and compared with PSO for optimal techno-economic design. • Ideal system can be identified as PV–WT–bio–battery stand-alone hybrid system with a cost of $581,218 and 0.254 $/kWh cost of energy.

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Table 2 (*continued*)

Author	Title	Key Findings
Zhu et al. (2019)	Solar accessibility in developing cities: A case study in Kowloon East, Hong Kong	• Promote integration of PV cells in the urban environment including on rooftops and building façades. • Reference work for the pre-design phase in urban planning. • Demand-driven analysis to predict usable locations assuming landscape of urban area will be reformed.
Arnaout et al. (2020)	Pilot study on building-integrated PV: Technical assessment and economic analysis	• Environmental plugin software integrated with building geometry modeling tool in 3D modeling software. Followed by detailed energy yield estimation software. • Eight BIPV systems ranging from 411.8 to 1085.6 kW were proposed. • Roof surface has the greatest energy potential between 548 and 1451 MWh yearly with a performance ratio from 78% to 85%. • Selected design generated 1415 MWh/year with a performance ratio of 84.9% (62.8% of saving).
Thadani and Go (This paper)	Integration of Solar Energy into Low-Cost Housing for Sustainable Development: Case Study in Developing Countries	• Pilot study to examine the feasibility of integrating green technology into low-cost housing. • Two case studies in selected developing countries with affordable housing problems. • Analyzed energy yield estimation with an energy modeling tool. • Comprehensive advanced energy system analysis with an energy layout tool. • Analyzed solar PV system parameters (tilt angle, PV modules, and optimizers) to prove impact on yearly energy yield. • Accessed economic and environmental implications of solar PV system designs for low-cost housing.

Gül, 2018). Alshammari and Asumadu studied four hybrid renewable energy systems (HRES) consisting of wind turbine (WT)–PV–biomass–battery systems to satisfy the electrical requirements of small rural communities. The authors used harmony search (HS) and particle swarm optimization (PSO) to evaluate the optimal sizing of the battery system. The results from the three algorithms were compared to investigate the most cost-efficient and reliable option. The PV–WT–bio–battery stand-alone hybrid system was recommended with the current cost of $581,218 and 0.254 $/kWh cost of energy. The PV–WT–battery hybrid system produced the lowest CO_2 emissions, whereas the WT–bio–battery hybrid system exhibited the highest carbon footprint (Alshammari and Asumadu, 2020).

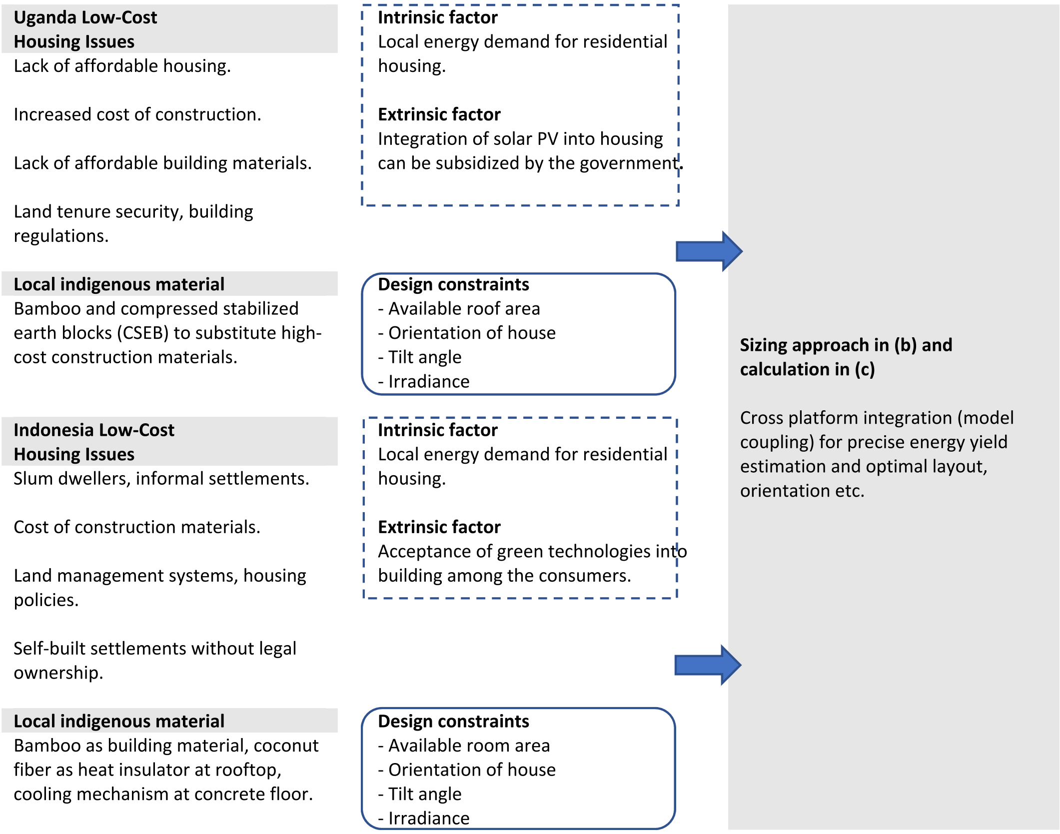
Lau et al. studied the solar energy potential in Dar es Salaam, Tanzania. They used a numerical model to study the solar radiation on roofs and facades, as it has been proven that urban structures affect the annual solar irradiance. The north- and south-facing building facades of high-rise buildings exhibit good potential for energy yield (Lau et al., 2017). Zhu et al. investigated solar accessibility in Kowloon East, Hong Kong. They developed a solar estimation model to identify solar accessibilities in developing cities, particularly dense cities with high-rise buildings. The model studied solar radiation at a particular elevation and azimuth. These urban surfaces were modeled as three-dimensional (3D) polygons through the creation of 3D shadow surfaces. The application of the estimation model can predict the solar accessibility at district scale (Zhu et al., 2019).

In addition to technological enhancement and research, several financial assistive schemes have been introduced nationwide to facilitate the expansion of renewable energy, particularly in the solar industry. The FiT scheme was introduced in Uganda in 2017. The Ugandan government obtained a mandate for FiT through the country's 2007 Renewable Energy Policy. The FiT scheme acted as an incentive to improve the use of modern renewable energy technologies from 4% to 61% of the total energy consumption by 2017 (Meyer-Renschhausen, 2013). The Global Energy Transfer Feed-in Tariff (GET FiT) Uganda was established to aid East African countries in achieving climate-robust low-carbon development. This initiative aims to mitigate climate change, reduce poverty, and encourage growth in these countries. The implementation of this program aims to (1) encourage investment from private bodies in renewable energy by improving the Renewable Energy FiT system and its application, (2) aid the stabilization of Ugandan finances of the power sector by adding low-cost generation capacity, (3) enable the Ugandan government to achieve ambitious electrification targets, (4) increase the availability of long-term commercial finance for projects in Uganda that involve small-scale renewable energy projects, and (5) further diversify the energy mix in Uganda, thereby improving security of supply (GET FiT Uganda Home, 2021).

In Indonesia, FiT has been implemented since 2009. The adaptation of FiT in Indonesia is very different from that in other countries. Initially, the Indonesian government allocated FiT only to small-scale hydropower sources. In 2010, biomass was included in the FiT list. The FiT on geothermal energy generators is discussed later. The FiT for solar energy commenced in 2013. The FiT in Indonesia differs depending on the number of islands and geographic location (Bakhtyar et al., 2013). Solar PV FiT is regulated by the Ministry of Energy and Mineral Resources (MEMR) Regulation No. 17, 2013, with an electricity rate of up to 0.30 US$/kWh (Yuliani, 2016). There are two solar PV schemes in Indonesia: the local tariff regulation that targets the developers to inject solar farm systems, and the latest one, which provides consumers an opportunity to contribute to the grid by installing solar PV systems in their homes. The new regulation encourages residential, industrial, or commercial consumers to install solar PV systems that can be connected to the grid. Consumers pay 65% of the electricity price for each kWh-exported PV energy (Adam and Miyauchi, 2019).

3. Methodology

There are intrinsic and extrinsic factors that strongly support the integration of solar PVs in low-cost housing in countries such as Uganda and Indonesia (Figure 4). In Uganda, local energy demand indicates a demand for supply in the residential sector. Installing a grid-connected solar PV system will be beneficial to home dwellers as there is a government subsidy for solar energy, and the energy can be sold to the grid, thereby benefiting the consumer. The main challenge in Uganda is to address the concerns regarding low-cost housing, which include a lack of affordable homes, high cost of construction, building materials that are not affordable, land tenure security, and building regulations. Local materials such as bamboo and CSEBs have been identified as alternatives to conventional construction materials. In Indonesia, the intrinsic factor that encourages the installation of solar PVs is the local demand for energy for housing, and the installation of solar PVs in low-cost homes can address this challenge. The extrinsic factor that encourages solar PV installation is the adoption of green energy in consumers' lifestyles. The local materials that can be used are bamboo and coconut fibers. The design constraints of installing a solar PV system are similar to those in Uganda. The design constraints of installing solar PV systems on these houses are the area of the roofs, orientation of the houses, tilt angle, and



Uganda Low-Cost Housing Issues

Lack of affordable housing.

Increased cost of construction.

Lack of affordable building materials.

Land tenure security, building regulations.

Local indigenous material

Bamboo and compressed stabilized earth blocks (CSEB) to substitute high-cost construction materials.

Intrinsic factor

Local energy demand for residential housing.

Extrinsic factor

Integration of solar PV into housing can be subsidized by the government.

Design constraints

- Available roof area
- Orientation of house
- Tilt angle
- Irradiance

Indonesia Low-Cost Housing Issues

Slum dwellers, informal settlements.

Cost of construction materials.

Land management systems, housing policies.

Self-built settlements without legal ownership.

Local indigenous material

Bamboo as building material, coconut fiber as heat insulator at rooftop, cooling mechanism at concrete floor.

Intrinsic factor

Local energy demand for residential housing.

Extrinsic factor

Acceptance of green technologies into building among the consumers.

Design constraints

- Available room area
- Orientation of house
- Tilt angle
- Irradiance

Sizing approach in (b) and calculation in (c)

Cross platform integration (model coupling) for precise energy yield estimation and optimal layout, orientation etc.

Figure 4. Overall flowchart of project rationale and methodology.

irradiance. The design constraints can be addressed by installing PV modules with higher nominal power, thereby overcoming space challenges. The tilt angle can be assessed to identify a suitable one, and the irradiation of the country is sufficiently high for solar PV installation.

The technical sizing of a BIPV system is a vital procedure. The conventional sizing approach was applied to the PV modules that were to be placed on the roof based on the energy modeling tool. Based on the climate scenario of Uganda and Indonesia, sizing assumptions were made. The sizing steps were as follows. At this stage of the project, a general concept of the BIPV configuration was expected. The energy modeling tool assisted in providing a suitable tilt angle, number of inverters, orientation of the panels, and the possible amount of power that can be generated. The technical sizing specifications followed the requirements based on IEA International Energy Agency (Berger et al., 2019) and IEC 63092: Photovoltaics on roof. The specified performance requirements have been integrated into the project:

i) Step 1: Site Location Screening

The possible sites were screened based on the coordinates of the proposed construction of low-cost houses in Uganda and Indonesia. The energy modeling tool identified the location using Google Maps to show a satellite view of the location.

ii) Step 2: Outlining the Roof Area

An energy modeling tool was used to plot the points on the roof. After this step, the modeling tool generated a suitable azimuth angle and tilt angle. Obstacles such as trees, HVAC systems, and ventilation systems were outlined to avoid PV cells from being placed in those locations. Identifying keep-outs ensured that power estimation was more accurate.

iii) Step 3: PV module layout and Setback

The setback rules that have been regulated by the local authorities must be followed when installing a PV rooftop system. The fire department of each country sets guidelines that must be abided if a fire occurs, i.e., setback values to ensure that there is sufficient space on the roof to provide access. The rules vary depending on the type of roof.

iv) Step 4: Selection of PV modules

The PV modules were selected based on their availability in Uganda and Indonesia. The average efficiency is a crucial parameter for the selection; the range of efficiency is between 16% and 20%. The module nominal power was considered during selection to ensure that the modules can support the demand of the dwellers. Some important information was obtained from the PV panels manufacturer. The specifications determine were under standard test conditions (STC). The maximum power ($P_{\max\_STC}$), maximum voltage (V_{MP_STC}), and maximum current (I_{MP_STC}) at maximum power were important details. To calculate the number of panels to be arranged in an array, we required the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), temperature coefficient for short-circuit current ($\mu_{I_{SC}}$), temperature coefficient for maximum power ($\mu_{P_{max}}$), temperature coefficient for open circuit voltage ($\mu_{V_{OC}}$), temperature coefficient at maximum power voltage ($\mu_{V_{MP}}$), and maximum allowable system voltage of the PV arrays. The dimensions of the panels are necessary when considering the space on the roof of the home. The length and width of the panels were provided by their respective manufacturers. STC is a wide industry standard for PV modules at a cell temperature of 25 °C, irradiance of 1000 W/m^2, and air mass of 1.5. Air mass is a measure of how much atmosphere the sun's rays have to penetrate as they travel to the surface of the earth. The air mass is directly related to solar radiation. The maximum open-circuit voltage of the PV modules ($V_{OC,max}$), maximum voltage at maximum power of the PV cells ($V_{MP,max}$), minimum voltage at maximum power ($V_{MP,min}$), and minimum voltage at maximum power after the voltage drop has been considered ($V_{min.VD}$) were computed to identify the utmost voltages of the PV cells.

v) Step 5: Selection of Inverters and Wiring

When the modules were placed on the rooftop, the electrical components were configured. The power and voltage were key parameters to consider when sizing the inverter. In an ideal scenario, the AC/DC ratio should range between 1.1 and 1.25 with consideration of the location and the solar irradiance. A string inverter is suitable when designing a residential PV system, as the modules are placed at a minimum of two different azimuths. The plane of array irradiance varies with each sun position; therefore, a string inverter or an inverter equipped with a maximum power point tracker (MPPT) is feasible. A micro-inverter and string inverter with multiple MPPTs can aid in reducing the mismatch losses of the array. The inverter was selected based on the specifications set by the manufacturer, such as the nominal PV power, ($P_{nom_{inverter}}$), maximum input voltage of inverter ($V_{Max_{inverter}}$), maximum and minimum MPP voltages ($V_{MPP,inverter}$ and $V_{MPP,main}$), and the nominal MPP voltage ($V_{MPP,nom}$).

The input voltage limit for the MPPT of the inverter was revised to ensure that the output voltage to the PV array did not exceed the allowable range of the input voltage into the inverter. The voltage revised was the maximum input voltage of the inverter ($V_{inv\_max\_rev}$), maximum input voltage limit in the MPPT of the inverter ($V_{MPPT\_max\_rev}$), and minimum revised input voltage limit to the MPPT inverter ($V_{MPPT\_min\_rev}$). From the Operation and Maintenance (O&M) perspective, the string inverter would also lower the O&M cost and is usually ideal for rooftops with limited space. Figures 5 and 6 highlight the key steps of this project.

This project was conducted in two stages: a) energy yield estimation and scoping, and b) detailed energy system design. In the first stage, the HelioScope software program was used to estimate the energy yield that can be obtained by installing PV modules on a roof. The modeling was performed on existing homes in Uganda and Indonesia. The PV array was configured, and suitable inverters, tilt angles, and orientations were determined. In the second stage, detailed energy system design and tilt angles with intervals of 5°, 10°,11°,12° and 15° were used to identify the suitable tilt angles for each country, respectively. Subsequently, the tilt angle was further scrutinized using smaller intervals to identify the optimal tilt angle. Next, five PV modules were tested with the optimal tilt angle to identify the PV module that generated the highest energy. When this was completed, the PV module was selected, and an optimizer was introduced into the PV system to study the possible improvement in the energy yield.

3.1. Energy yield estimation and scoping

In this stage, the energy modeling tool was used to understand the layout and technical parameters of the PV system. This was a preliminary

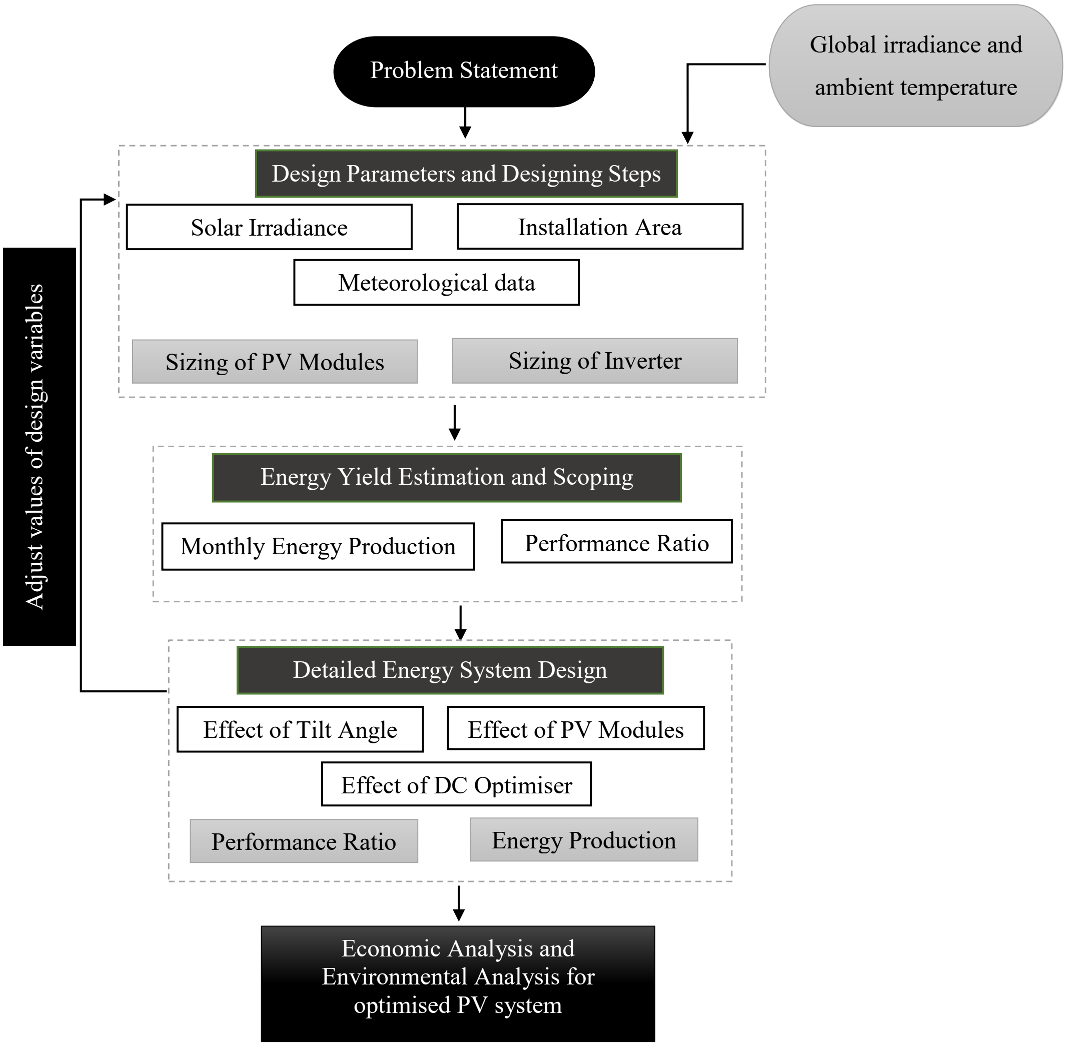


Figure 5. Detailed sizing procedures and stages.

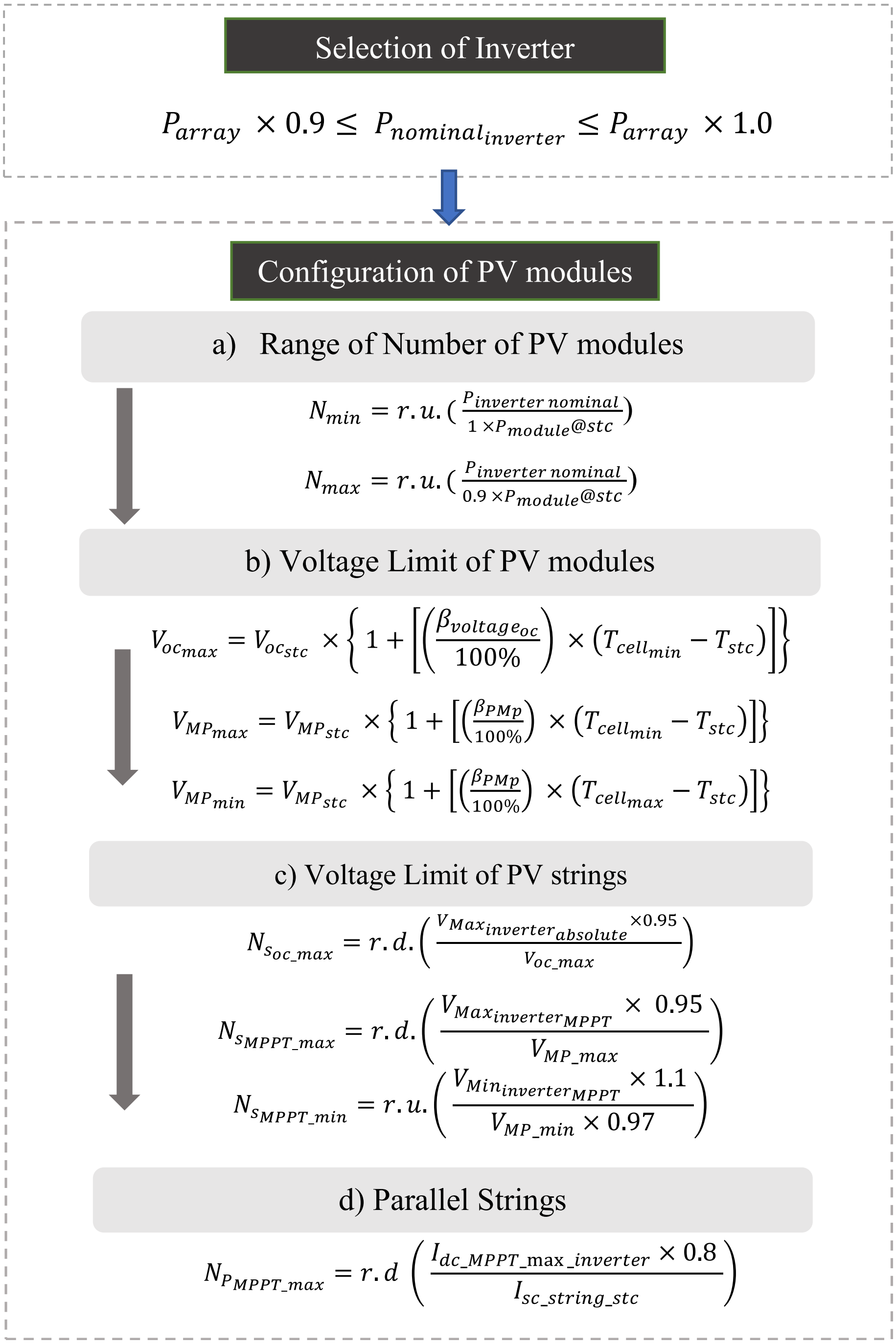


Figure 6. Calculations and equations involved.

stage for estimating the amount of energy that can be produced by a household. The two locations that were studied were Bantul, Yogyakarta, Indonesia, and Bukalango, Kampala, Uganda. Tables 3 and 4 list the design configurations of solar PV systems. The design parameters in this study were the tilt angle (18°), type of PV module used, inverter, and the presence of an optimizer. The performance parameters used to evaluate the PV system were the system yield and performance ratio. The performance ratio was the measured output of the system over the expected output of the system.

3.2. Detailed energy system design

The PV system was further analyzed to understand the nature of the sun position and identify the suitable tilt angle and the PV module to be used in Bantul and Bukalango, respectively. The sun path diagrams of the mentioned sites are shown in Figures 7 and 8. The specifications of the PV system that were tested are listed in Tables 5 and 6. The systems were tested based on tilt angles and PV modules. The final suitable configuration specifications were tabulated.

Array losses are any losses that inhibit the PV cell from producing its nominal power, as suggested by the manufacturer under standard conditions. There are many losses within this category, including shading losses, incidence angle modifier (IAM), irradiance loss, mismatch losses, and ohmic wiring losses. The IAM losses are calculated based on Fresnel's law. This law describes the transmission and reflection of electromagnetic radiation when it touches an interface with different optical media. The mismatch losses are due to the lowest current driving the entire string of a string of PV cells. PV modules should be arranged according to

Table 3. (a) & (b): Design specifications for preliminary scoping of Bantul, Yogyakarta.

(a)

Specifications of Bantul, Yogyakarta	
Irradiance	kWh/m^2
Energy	kWh
Racking	Flush Mount
Setback	8 ft
DC/AC ratio	0.72 (Design 1),0.65 (Design 2),1.02 (Design 3)
Weather Dataset	TMY, 10 km Grid, meteonorm
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Soiling	2 %
Irradiance Variance	5 %
Cell Temperature Spread	4 °C
Module Binning Range	−2.5%–2.5%
AC System Derate	0.50%

(b)

Technical Specifications	Design 1	Design 2	Design 3
Modules	Total: 30 (8.63 kW)	Total: 29 (9.14 kW)	Total: 30 (9.9 kW)
Inverters	AE6.0 (277 V) Total: 2 (12.0 kW)	NAC75K-DS (Renac) Total: 2 (14.0 kW)	AE5.0 (277 V) Total: 2 (9.66 kW)
String Wiring	10 AWG (Copper) Total: 3 (5.1 m)	10 AWG (Copper) Total: 3 (28.7 m)	10 AWG (Copper) Total: 3 (23.7 m)
Optimizers	V750-13.5 Total: 3 (19.0 kW)	–	V750-13.5 Total: 3 (28.5 kW)
Cells per String	8–13	8–13	8–13
AC Home Runs	–	12 AWG (Copper) Total: 2 (11.2 m)	12 AWG (Copper) Total: 2 (10.6 m)
AC Home Runs	–	500 mm^2 (Copper) Total: 3 (20.9 m)	500 mm^2 (Copper) Total: 3 (32.3 m)
AC Panels	–	–	2 input AC Panel Total: 1
Home Runs	12 AWG (Copper) Total: 2 (26.0 m)	–	–
Combiners	1 Input combiner Total: 2	–	–

the maximum power current to reduce mismatch losses. The ohmic wiring losses occur between the available power from the cells and the power at the terminals of the subarray.

3.3. Economical analysis

The Levelized Cost of Electricity (LCOE) can be estimated using the initial cost of installation and the annual operating costs for the cost of produced energy. The long term profitability of the project can be calculated based on the initial costs, yearly charges, financial parameters and tariffs etc as shown in Table 7(a). For example, solar PV feed-in tarrif rates depend on the type renewable energy technology, installed capacity and effective period etc (FiT Rates, 2020). The Net Present Value (NPV), payback period and the Return of Investment (ROI) ratio are the important indicators in the economic evaluation. The payback period is the number of years needed to recover the cost of the investment of the project which is defined in the installation and operation cost (PVSyst).

Table 4. (a) & (b): Design specifications for preliminary scoping of Bukalango, Kampala.

(a)

Specifications of Bukalonga, Kampala	
Irradiance	kWh/m^2
Energy	kWh
Racking	Flush Mount
DC/AC ratio	0.54 (Design 1), 0.81 (Design 2), 0.92 (Design 3)
Weather Dataset	TMY, 10 km Grid, meteonorm
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Soiling	2 %
Irradiance Variance	5 %
Cell Temperature Spread	4 °C
Module Binning Range	−2.5%–2.5%
AC System Derate	0.50%

(b)

Technical Specifications	Design 1	Design 2	Design 3
Modules	Total: 183 (5.41 kW)	Total: 22 (7.26 kW)	Total: 25 (8.25 kW)
Inverters	Protect PV 10 (AEG Power Solutions) Total: 1 (10.0 kW)	AE5.0 (208 V) Total: 2 (8.94 kW)	AE5.0 (208 V) Total: 2 (8.94 kW)
String Wiring	10 AWG (Copper) Total: 1 (1.0 m)	10 AWG (Copper) Total: 2 (3.3 m)	10 AWG (Copper) Total: 3 (3.2 m)
Optimizers	V750-13.5 Total: 2 (19.0 kW)	–	–
Cells per String	75–238	10–14	10–14

The payback period is undefined if the system is not profitable. The payback period can be defined as:

$$\begin{aligned} &Recovered\ amount\ for\ year\ t = Net\ balance\ of\ year\ t \\ &\quad + Self\ consumption\ saving\ for\ year\ t \\ &\quad + Redemption\ part\ of\ the\ loan\ for\ year\ t \end{aligned}$$

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

R_t = Net balance (income-expenses) for the year (t)
i = Discount rate that could be earned in alternative investments
n = Lifetime of the system

The Return of Investment (ROI) is the ratio of the net benefit to the initial investment which measures system profitability (PVSyst). A negative ROI proves the system is not profitable. The ROI is calculated as such:

$$ROI\ ratio = \frac{Net\ benefit\ at\ the\ end\ of\ lifetime}{Total\ investment} \tag{2}$$

4. Results and discussions

From the energy yield estimation (stage 1) and advanced system analysis (stage 2), the results were obtained to identify the optimal scenario of the PV arrangement to be fitted on the rooftops in Uganda and Indonesia. The parameters used were maintained as strictly as possible to the actual scenario. In stage 1 for Bukalango, Kampala (Uganda), and Bantul, Yogyakarta (Indonesia), the estimation was

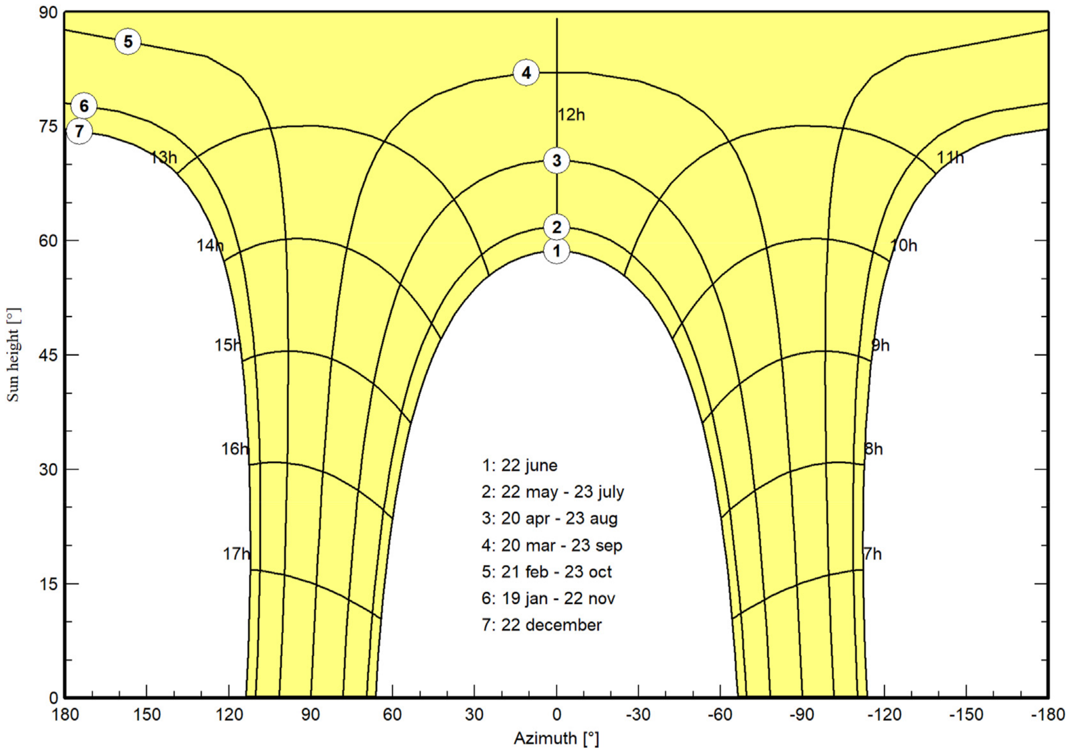


Figure 7. Sun path of Bantul, Yogyakarta.

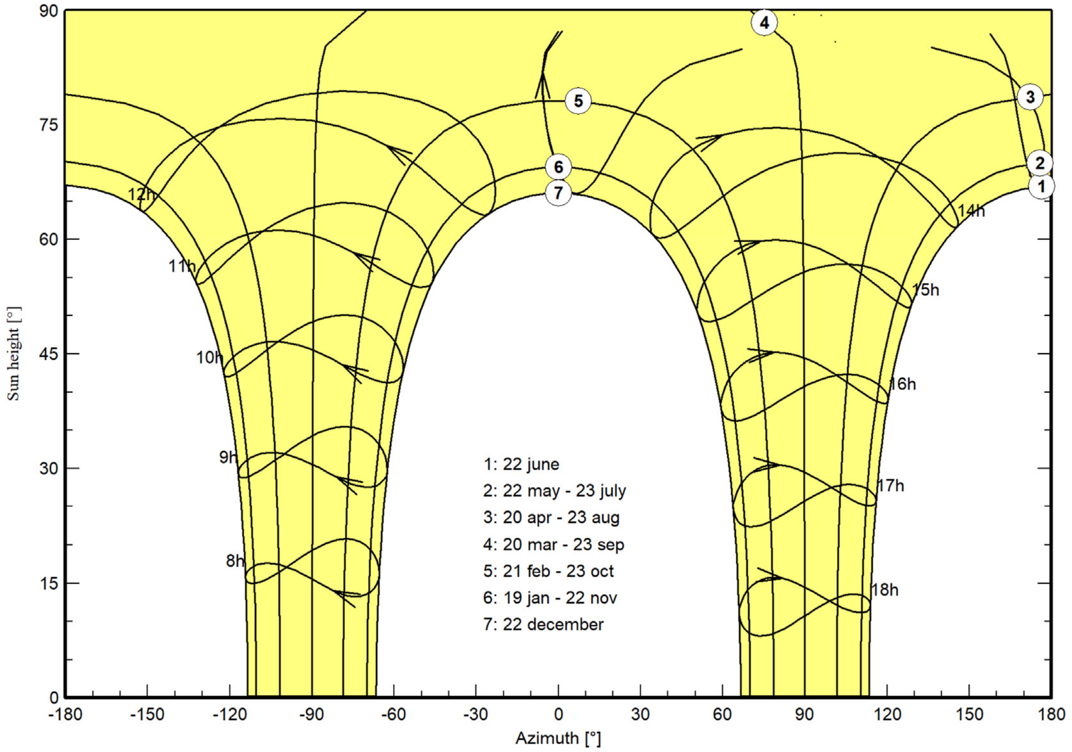


Figure 8. Sun path of Bukalango, Kampala.

conducted using a roof image. The layout of the PV system was designed to fit the roof specifications. Figure 9 summarizes the monthly production of the three proposed designs for Bukalango. Based on the chart, Design 3 had the highest production of energy, which is an annual production of 11.14 MWh. Design 1 and 2 had annual productions of 7.098 and 9.761 MWh, respectively. Based on Design 3, the

Table 5. Specifications for Bantul, Yogyakarta.

Bantul, Yogyakarta	
Field type	2 Orientations
Plane tilt	12°
Azimuth	−90°/90°
Optimization	Yearly irradiation yield
Ohmic losses	STC losses – 2.0 %
Ageing	Degradation factor as PV cell datasheet
No of Modules	20
Inverter	CSI-3KTL1P-GI-FL (without optimiser) AS-IR01-4000 (400kW) (with optimiser)

Table 6. Specifications for Bukalango, Kampala.

Bukalango, Kampala	
Field type	2 Orientations
Plane tilt	12°
Azimuth	−90°/90°
Optimization	Yearly irradiation yield
Ohmic losses	STC losses 2.0 %
Ageing	Degradation factor as PV cell datasheet
No of Modules	20
Inverter	BPT-S 3.68 (without optimiser) AS-IR01-4000 (400kW) (with optimiser)

Table 7a. Summary of economical input parameters (Teo and Go, 2021) (ENFSolar).

Features	Values
Solar PV	
Capacity	8.2 kW
Capital (US$/Wp)	0.21 to 0.61
Replacement (US$/Wp)	0.21 to 0.61
Operation and Maintenance (US$/Wp)	0.10
Inverter	
Capacity	7.40 kW
Capital (US$/Wp)	0.244
Operation and Maintenance (US$/Wp)	0.20
Quantity	20
Capital (US$/piece)	45

average performance ratio was 77% and had 25 PV cells connected to two inverters. Design 3 was the recommended PV design system, and the configuration of the PV cells is shown in Figure 10. Figure 11 shows a summary of the monthly production of energy for the three designs in Bantul. Design 3 had the highest annual production of energy of 12.67 MWh. Designs 1 and 2 had annual productions of 10.28 and 11.45 MWh, respectively. The layout of Design 3 is shown in Figure 12. Based on Design 3, the average performance ratio was 75.5% and had 30 PV cells connected to two inverters.

In the advanced system analysis stage (stage 2), the effects of varied tilt angle, PV module modal, and the effect of an optimizer on the PV system were examined.

a) Effect of Tilt Angle on PV system Performance

The tilt angle has a significant effect on the output performance of the PV modules. The solar PV energy output can be increased by up to 20% when the panel is placed at an optimal tilt angle compared with a horizontal orientation. The tilt angles tested ranged from 5°, 10°, 11°, 12°, and 15°. The range of the tilt angle was selected to identify a tilt angle that can maximize production and ease the cleaning of the PV panels. The performance ratios of the PV systems for Bukalango, Kampala (Uganda) are shown in Figure 13. The measured performance ratio ranged from 79% to 80%. Table 7(b) shows the system production, system losses, array losses, and module losses of the seven simulated systems. The performance ratios of the PV systems for Bantul, Yogykarta (Indonesia) are shown in Figure 14. The performance ratio ranged from 80% to 81%. The operating conditions of both PV systems were 50 °C.

Table 8 shows the system production, system losses, array losses, and module losses of the seven simulated systems. As observed, the ideal tilt angle was 5° as it had the highest production, but to avoid the accumulation of dust on the panels, a higher tilt angle of 12° was selected. The tilt angle must be considered based on several factors, such as energy yield, installation, and cleaning.

b) Effect of PV module designs on PV system performance

Various solar PV modules available on the market are suitable for residential buildings. The variety has a range of efficiencies and nominal powers that provide the desired output of power. Generally, in Indonesia, a household consumes 245 TWh of energy annually (Enerdata, 2019), and in Uganda, the corresponding amount is approximately 28 TWh (as per 2016) (Ritchie and Sierocuk, 2001). The performance ratios of the system with five PV cell models are listed in Tables 9 and 10 for each location. The types of PV modules, nominal power, efficiency, and overall system production are listed in Tables 9 and 10. Table 9 indicates that PV cell 5 generated the highest yearly energy with 10 cells arranged in series on both sides of the roof. Figure 15 shows the distribution of energy and performance ratio for the entire year of the five types of PV cells for Bukalango. For Bantul, PV cell 5 provided the highest yearly energy production, but the performance ratio of PV cell 1 was better. The cells were arranged in a series of 10 on each side of the roof. Figure 16 shows the distribution of energy and performance ratio for the entire year based on all five PV cells for Bantul.

c) Effect of optimizer on PV system production

The use of an optimizer can further improve the system's production and design. The optimizer aids in optimization, monitoring, and shutdown. The inclusion of an optimizer increases the shade and mismatch tolerance, enhances the energy yield, maximizes roof usage, and provides greater design flexibility. The monitoring system enables the detection of any fault at the module level, and it can be rapidly attended to. The shutdown function enables the system to be switched off at the module level. Based on the recommended tilt angle of 12° and PV module that was suited to an optimizer (PV cell 4), the system was further improved with the inclusion of an optimizer. The optimizer converted each module converts into a smart module to produce the maximum energy by constantly tracking the MPPT of each module. The tracking of the MPPT of each module increased the efficiency of the DC power entering the inverter. The amount of energy produced annually increased from 11583 to 11648 kWh/year, which was an increase of 0.5%. The performance ratio of the system increased from 81.2% to 81.6%. Figure 17 shows the PV system output in terms of the global incidence in the collector panel, performance ratio, and energy yield for Bukalango. For Bantul, the optimizer was integrated with a PV system with PV cell 4. The optimizer increased the yearly energy production from 11038 to 11623 kWh/year, which was a 5.3% increase. The performance ratio of the system increased from 79.3% to 83.5%. Figure 18 shows the PV system output in terms of the global incidence in the collector panel, performance ratio, and energy yield for Bantul.

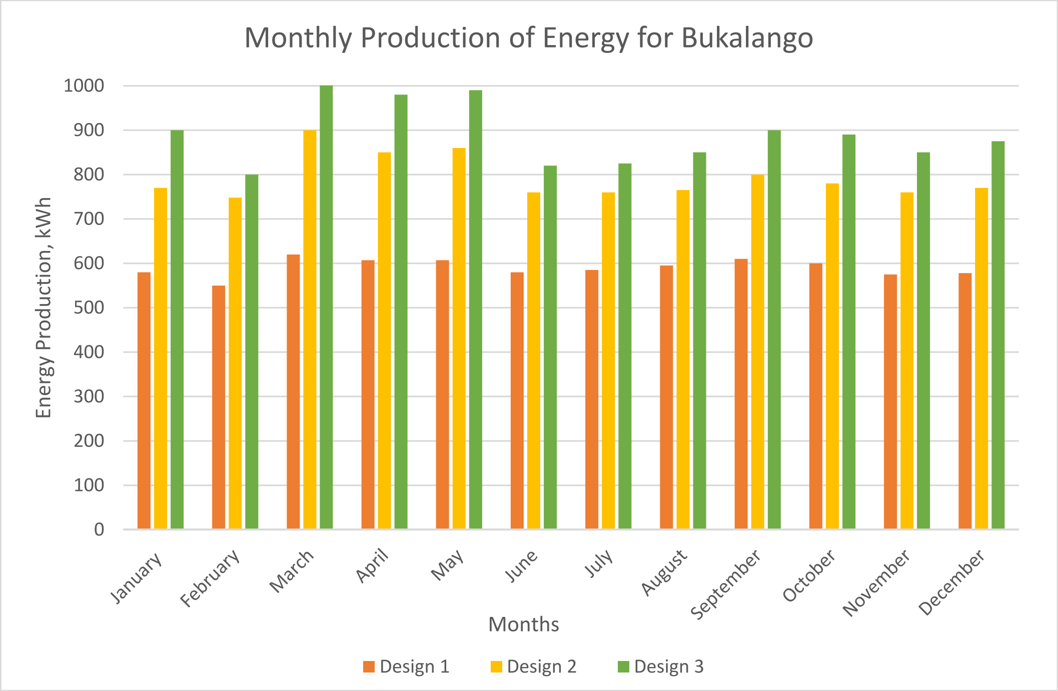


Figure 9. Monthly energy production per house for Bukalango, Kampala, Uganda.

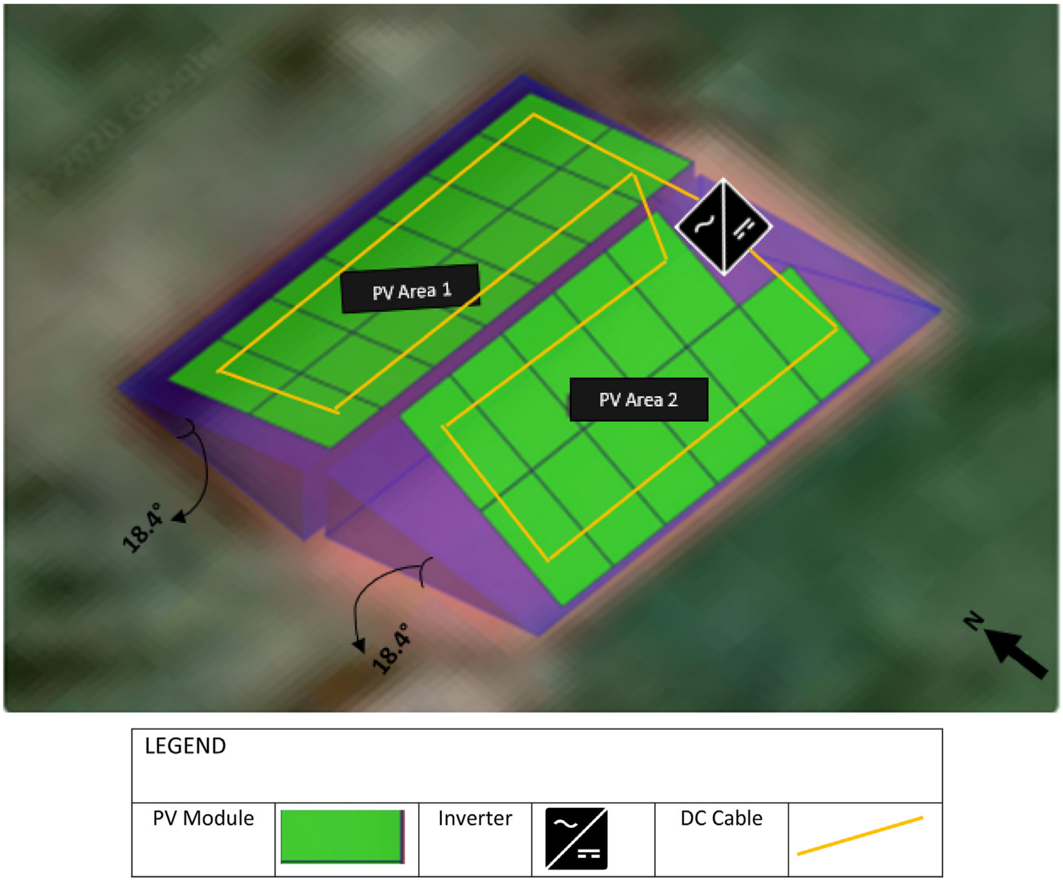


Figure 10. Southwestern angle of design 3 layout for Bukalango, Kampala, Uganda.

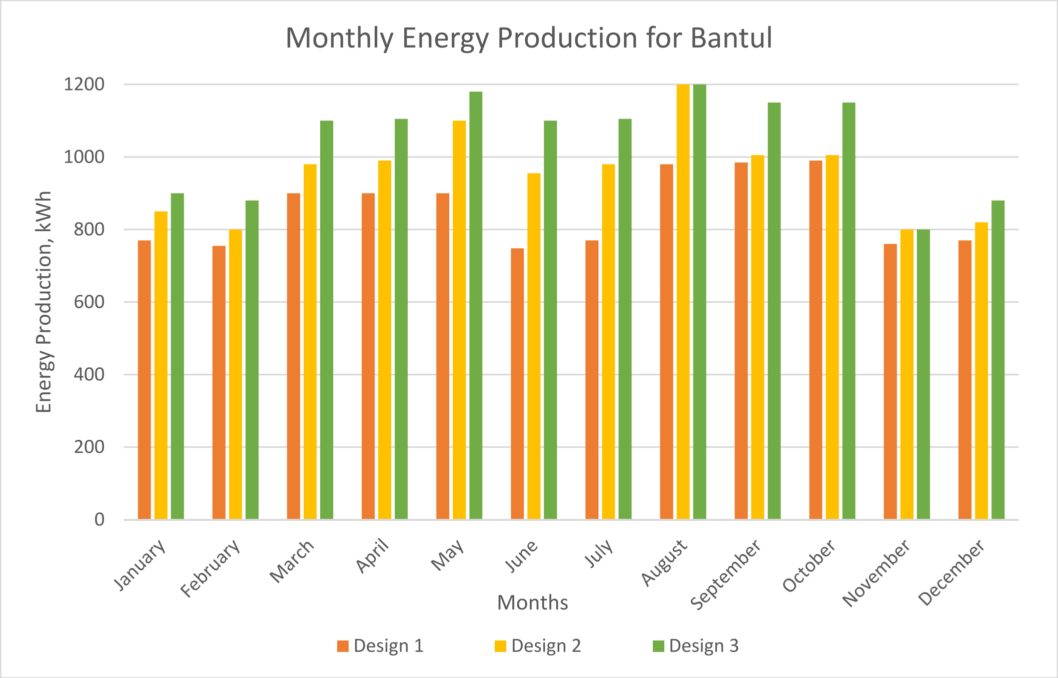


Figure 11. Monthly energy production per house for Bantul, Yogyakarta, Indonesia.

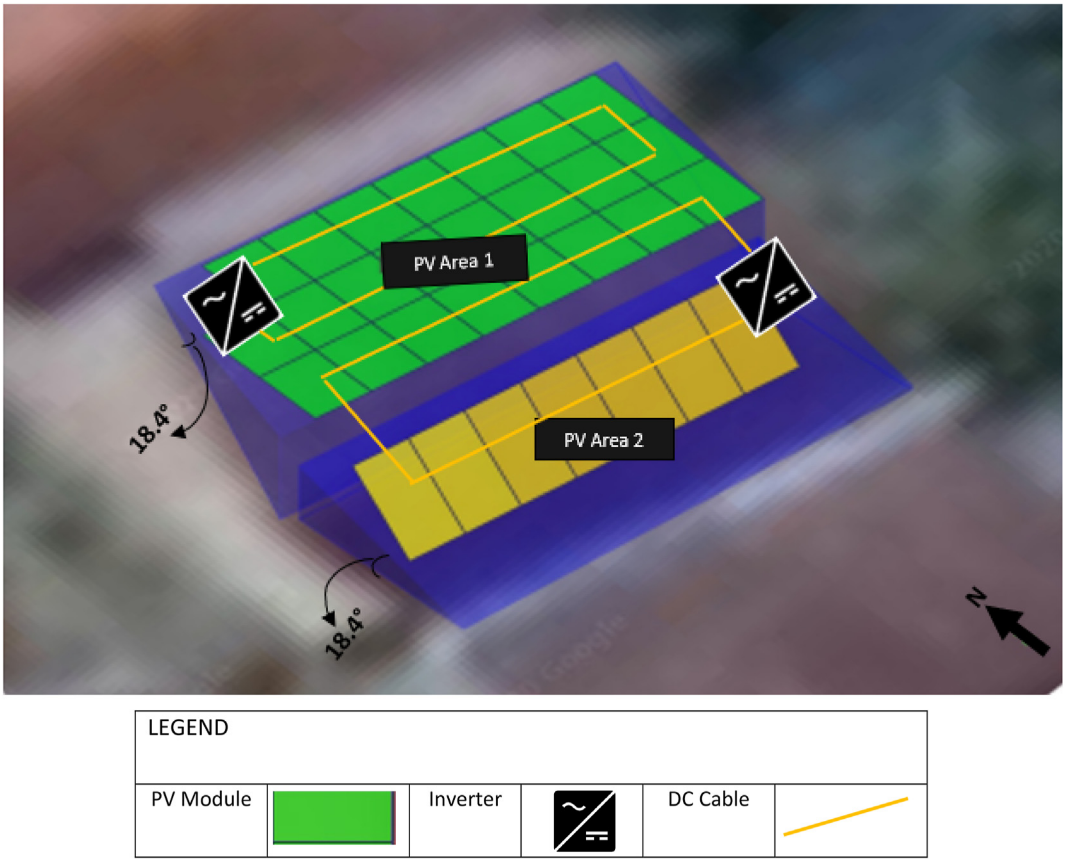


Figure 12. Southwestern angle of design 3 layout for Bantul, Yogyakarta, Indonesia.

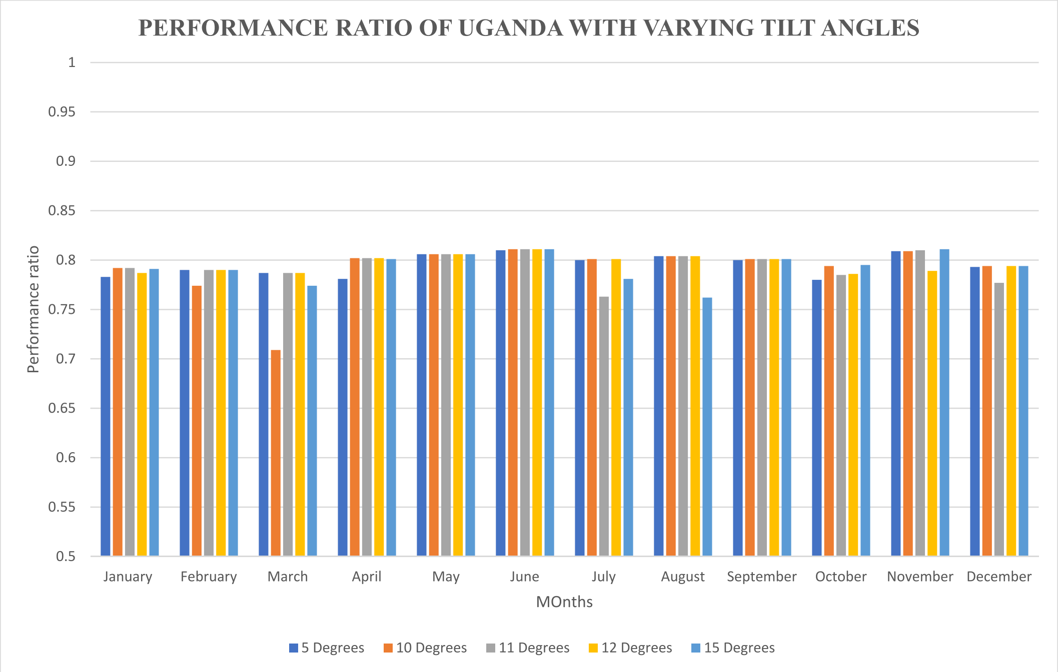


Figure 13. PR of Bukalango, Kampala, Uganda with Varying Tilt angles.

Table 7b. System results for Bukalango, Kampala, Uganda for varying tilt angles.

Tilt Angle (°)	PR (%)	System Production (kWh/yr)	Array Losses	System Losses	Module Loss
5	79.5	8883	0.77	0.25	0.3
10	79.1	8778	0.76	0.27	0.3
11	79.4	8798	0.76	0.25	0.5
12	79.6	8806	0.75	0.24	0.9
15	79.3	8713	0.75	0.26	1.1

Table 8. System results for Bantul, Yogyakarta, Indonesia for varying tilt angles.

Tilt Angle (°)	PR (%)	System Production (kWh/yr)	Array Losses	System Losses	Module Loss
5	80.1	9301	0.8	0.15	0.1
10	80.5	9287	0.8	0.14	0.5
11	80.6	9279	0.79	0.13	0.7
12	80.6	9264	0.79	0.13	0.7
15	80.5	9186	0.78	0.14	1.4

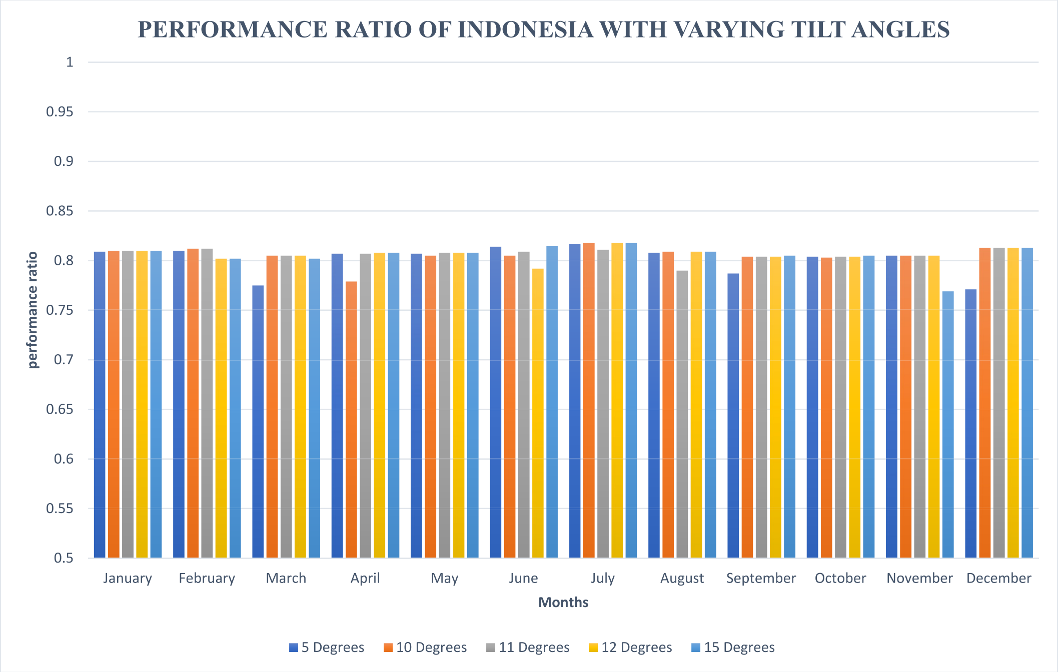


Figure 14. Performance ratio of Bantul, Yogyakarta, Indonesia with varying tilt angle.

Table 9. PV Cells specifications for Bukalango, Kampala, Uganda.

Design	Type of PV module	Nominal Power (Wp)	Efficiency (%)	PR (%)	System Production (kWh/yr)
1	Si-mono	345	17.78	81.9	10079
2	Si-poly	345	17.78	81.9	10076
3	Si-mono	390	19.38	82.9	11529
4		400	19.9	82.7	11583
5		410	20.38	83.4	12199

Table 10. PV Cells specifications for Bantul, Yogyakarta, Indonesia.

Design	Type of PV module	Nominal Power (Wp)	Efficiency (%)	PR (%)	System Production (kWh/yr)
1	Si-mono	400	19.42	82.2	11451
2		400	19.95	79.7	11101
3		405	20.22	79.8	11251
4		400	19.86	79.3	11038
5		410	20.5	80.4	11475

4.1. Economic and environmental analysis

The levelized cost of electricity (LCOE) was used to evaluate the economic feasibility of the project. A system with and without the optimizer was evaluated economically for comparison. For Bukalango, the LCOE was $0.262/kWh for the system incorporated with an optimizer and had a payback period of 4.6 years. Uganda's FiT is $0.362/kWh for solar PV technology. For the system without an optimizer, the LCOE was $0.257/kWh with a payback period of 4.6 years. For Indonesia, the FiT is $0.3/kWh for solar PV technology. The LCOE for the system with the optimizer was $0.278/kWh with a payback period of 13.1 years. For the system without an optimizer, the LCOE was $0.292/kWh with a payback period of 19.1 years. The carbon balance of the system was calculated based on the lifecycle emissions calculation and Environmental Impact Assessment of each country. The amount of carbon dioxide reduction from one home that installed solar PV was 173.894 t in Indonesia and 122.742 t in Uganda. The carbon balance tool calculated the amount of carbon dioxide that could be reduced based on the assumption that the PV installation will replace the electricity supplied by the existing grid.

4.2. Comparative studies

Table 11 shows the differences and similarities between the design parameters, performance parameters, and economic and environmental parameters of the two sites. The performance parameters and economic and environmental parameters were different as the meteorological data of these countries vary (i.e., solar irradiance and temperature).

Based on a study by Widodo et al. on the potential of solar energy in residential rooftop surface area in Semarang City, Indonesia, the PV modules used in this study had a nominal power of 200 Wp and an area of 1.487 m × 0.992 m (Widodo et al., 2020). In this study, we used PV modules with a nominal power of 400 Wp and an area of 2.015 m × 1.000 m. The study conducted by Widodo et al. evaluated the potential of energy that can be produced annually based on 16 sub-districts of Semarang. The results range from 44,051 to 222,222 MWh/year, depending on the available roof area of the houses. We can conclude that the higher the number of modules, the higher the energy production. Based on the study conducted in Bantul, Yogyakarta, the number of panels was fixed at 20 because the project was preliminary and can be accommodated to the requirements of low-cost homes. To optimize the production of energy, we considered the tilt angle, type of PV module, and installation of optimizers to ensure better production. The final design had an energy production of 11623 kWh/year for each house.

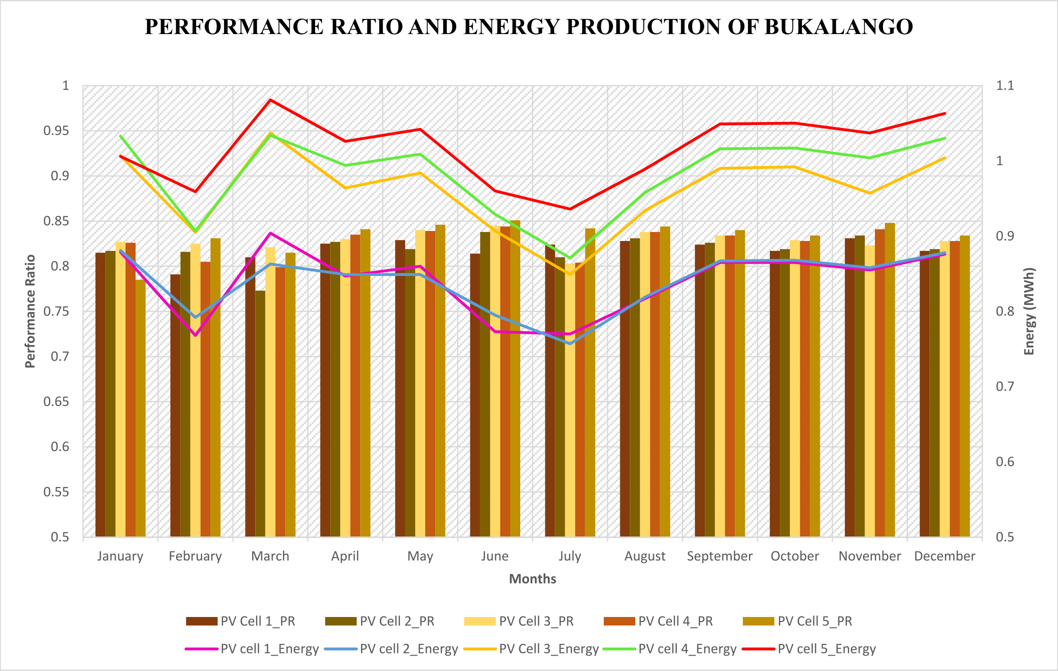


Figure 15. Performance ratio and energy production of Bukalango, Kampala, Uganda.

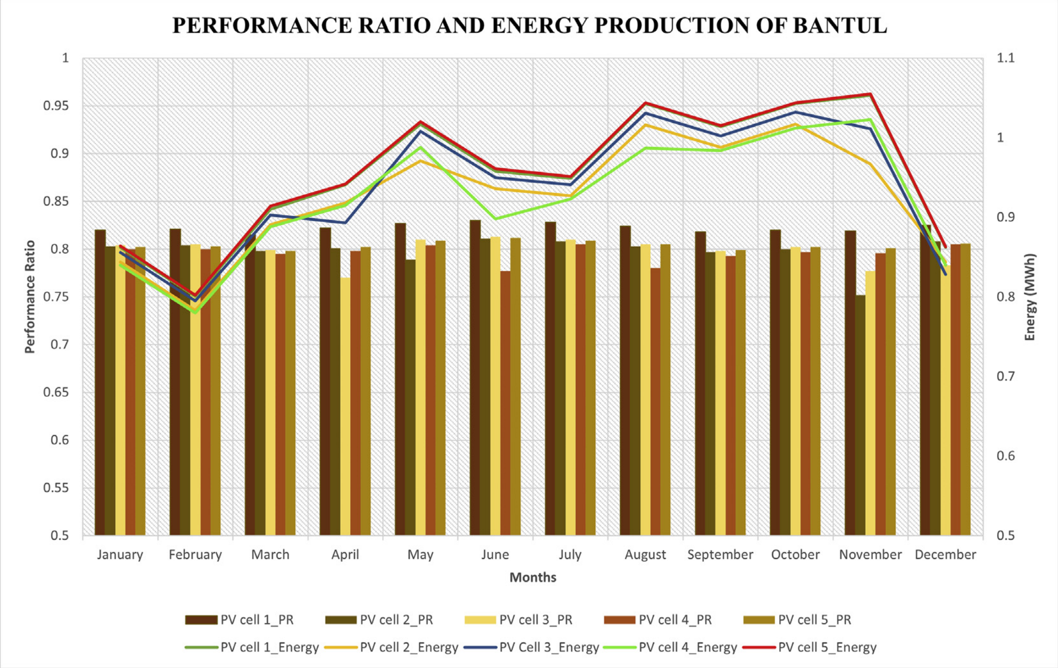


Figure 16. Performance ratio and energy production of Bantul, Yogyakarta, Indonesia.

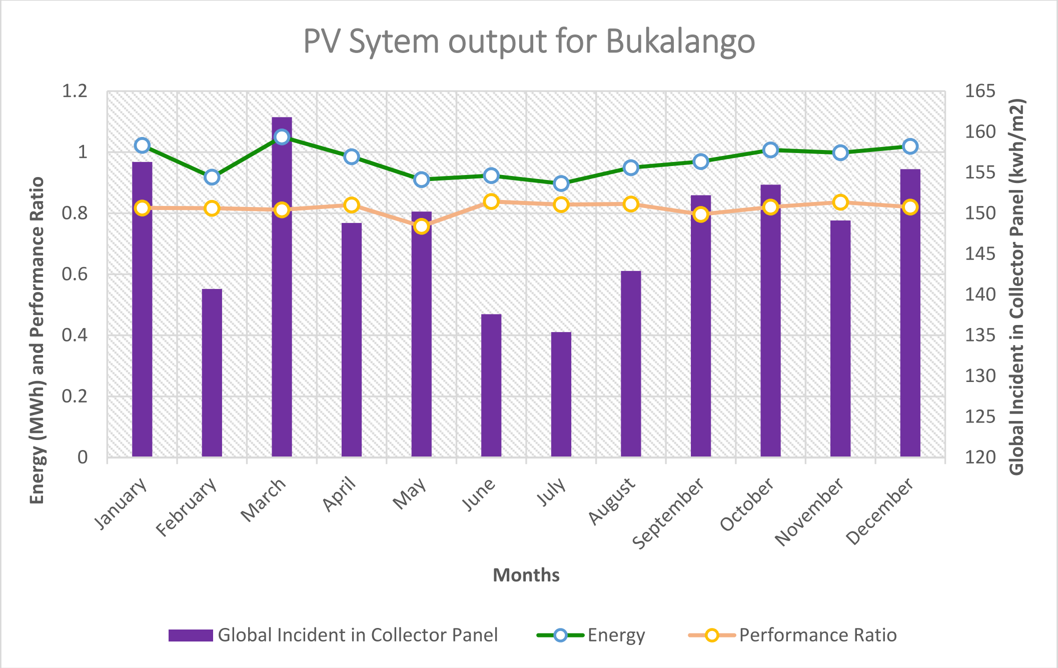


Figure 17. PV System output for Bukalango, Kampala, Uganda.

Ziuku and Meyer studied the potential for implementing BIPV systems in the housing sector in South Africa. This project was conducted with a heterojunction with intrinsic thin-layer modules with a nominal power of 190 Wp. Twenty modules were used, with dimensions of 1.319 m × 0.880 m each (Ziuku and Meyer, 2013). In this study, modules of Si-mono type and nominal power of 400 Wp were used for Uganda. The area of these modules was 2.015 m × 1.000 m. Twenty modules were used for each house. Ziuku and Meyer's project results demonstrated that the measured energy of the array was 11.6 kWh/day and the payback period was 8 years. For the project conducted in Uganda, the energy yield was 11648 kWh/year with a payback period of 4.6 years.

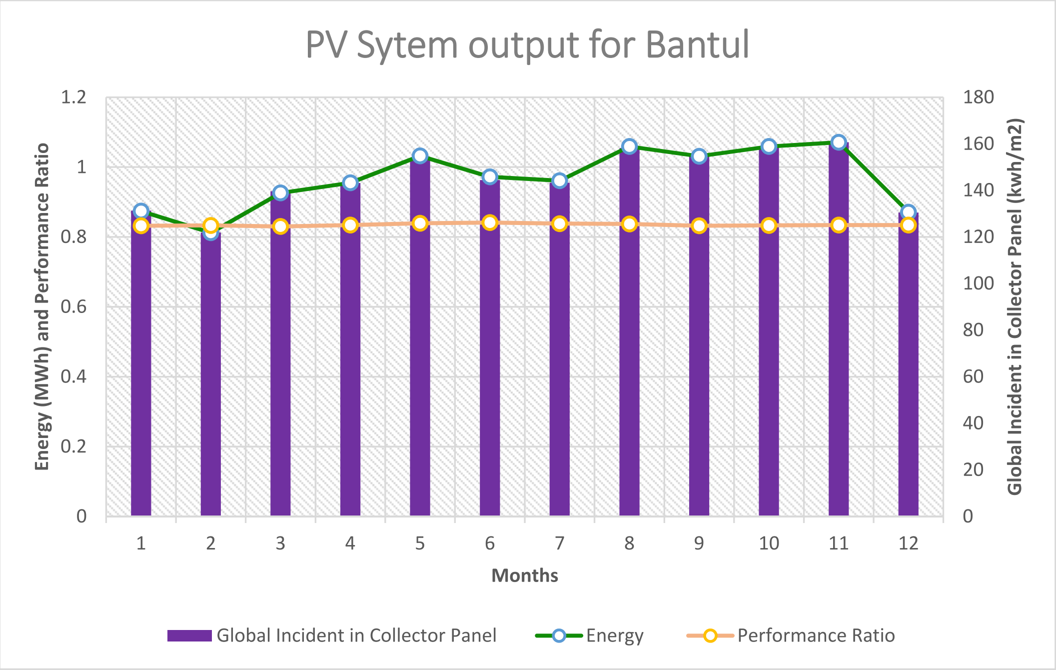


Figure 18. PV System output for Bantul, Yogyakarta, Indonesia.

Table 11. Similarities and Differences of final design between Two Sites Bukalango, Uganda and Bantul, Indonesia.

	Uganda	Indonesia
Design Parameters		
Type of PV module	Si-Mono	Si-mono
Tilt Angle (°)	12	12
Performance Parameter		
Performance Ratio (%)	81.6	83.5
Yearly Yield (kWh/year)	11648	11623
Economic and Environmental Parameter		
LCOE ($/kWh)	0.257	0.278
Carbon Dioxide Reduction (tons)	122.742	173.894

5. Conclusion

The demand for affordable housing in Uganda has increased significantly because of the increase in the low-income population. These shortcomings are due to elevated land and construction material costs, lack of land tenure security, and stringent building regulations. Affordable housing provided by the government is significantly cheaper than that by private-sector developers. The integration of solar PV into housing can also be subsidized by the government, which is aligned with the Ugandan government's initiative to increase renewable energy share to 61% by 2017 and electricity access to 22% by 2022. For Indonesia, housing prices have been increasing uncontrollably owing to the lack of government policies and market control. Housing prices are controlled by real estate developers and vary. Research has shown that the integration of green technologies in housing development is well accepted by consumers. This is aligned with Indonesia's National Energy General plan to ensure a high penetration of solar energy in the country.

The research findings indicate that integrating solar energy into low-cost housing is a feasible option. The energy yield estimation stage has proven effective in understanding the optimal configurations of the design parameters and solar PV layout on the rooftop. For Bukalango and Bantul, our Design 3 for both countries produced the highest energy yield for the year, which were 11.14 and 12.67 MWh, respectively. In the advanced system analysis stage, we further investigated the tilt angle, PV module types, and the effectiveness of the optimizer. The tilt angle suitable for a residential PV system was 12° in both locations. Integrating an optimizer in the system significantly increased the energy yield. The system performance improvement achieved was 0.5% and 5.3% in Uganda and Indonesia, respectively. The economic analysis results proved that the proposed configurations are economically viable in both locations. For Bukalango, the LCOE with and without an optimizer ranged from $0.25/kWh to $0.36/kWh. For Bantul, the LCOE ranged from $0.25/kWh to $0.3/kWh.

Based on these findings, we can conclude that installing a solar PV system is feasible and economically affordable. Installing a PV system with an optimizer increases the energy yield and ensures that the PV system is fully monitored and maintained. This prolongs the lifetime of the PV system. The overall cost can be further reduced by adopting local indigenous materials. We investigated the feasibility of adopting bamboo and CSEBs to substitute high-cost construction materials. Several governmental plans to promote the adoption of bamboo have been implemented in Indonesia. Local material adoption is expected to reduce the dependence on synthetic materials and time of transporting the building materials. More alternative materials that are suitable for wet tropical areas can be explored via ecological building materials. These local indigenous materials are expected to replace conventional materials by stages.

This research outcome is aligned with Indonesia's National Energy General plan to mandate 25% of rooftops to be installed with solar PVs. This also contributes to the national initiative of Uganda in Sustainable Energy for All (SE4All) to encourage the utilization of solar energy as part of sustainable development. The Ugandan government mandated the FiT scheme across the country under the 2007 Renewable Energy Policy. This initiative aimed to mitigate climate change, reduce poverty, and encourage growth in these countries. This program also enabled the Ugandan government to achieve electrification targets and increase the availability of long-term commercial finance for small-scale renewable energy projects. In Indonesia, FiT has been implemented since 2009. These include local tariff regulations that target developers to inject solar farm systems and the latest ones, which provides consumers an opportunity to contribute to the grid by installing solar PV systems in their homes. New regulations encourage residential, industrial, or commercial consumers to install solar PV systems that can be connected to the grid. With support from the government, the proposed model can be replicated in countries with similar climate conditions, and solar energy can be incorporated into low-cost housing.

Declarations

Author contribution statement

Hashwini Lalchand Thadani: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Go Yun Ii: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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