

Optimization of On-Grid Solar Power Plant Design for Urban Residential Areas: Case Study in Indonesia

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ABSTRACT

The increasing demand for electricity in urban areas of Indonesia demands diversification of sustainable energy sources. On-grid Solar Power Plants (PLTS) are a strategic alternative to reduce dependence on fossil fuels and increase household energy resilience. However, optimizing PLTS design still faces technical and structural challenges, such as the mismatch between panel production capacity and electricity consumption patterns, limited space, and weak regulatory support and fiscal incentives. This study uses a qualitative approach with a case study in an urban housing complex to examine the design process, implementation, and obstacles of on-grid PLTS. Data were obtained through in-depth interviews, field observations, and studies of policy and technical documents. The results of the study indicate that the success of PLTS implementation is highly dependent on a design that is contextual to the technical and social characteristics of housing, the support of fiscal policies such as initial subsidies, and institutional integration between communities, local governments, and the private sector. In addition, community-based approaches such as energy cooperatives can increase inclusive system adoption. This study concludes that on-grid PLTS is not only a technical solution for the clean energy transition, but also an instrument of socio-economic transformation that requires multidimensional synergy in its implementation in the urban environment of Indonesia.

Keywords: Solar Power Plant Design; Renewable Energy; Urban Housing

INTRODUCTION

The need for electricity in urban areas in Indonesia has increased non-linearly along with rapid urbanization and industrialization. Data from the National Energy General Plan (RUEN) shows that the household sector contributes around 40% of the total national electricity consumption, making it a crucial sector in the national energy security strategy (Ministry of Energy and Mineral Resources, 2023). However, dependence on fossil fuel-based power plants such as coal and natural gas is a major obstacle to realizing a sustainable energy system. In addition to causing air pollution and increasing carbon emissions, this model is also very vulnerable to fluctuations in global energy prices, thus burdening the state budget and society.

Furthermore, the inequality in the distribution of electricity supply is also an unresolved structural problem. Although the PLN electricity network has reached most urban areas, the quality and reliability of its supply are still often complained about, especially during peak loads. This shows that the existing electricity system is not fully capable of responding to the dynamics of ever-changing demand. Therefore, the development of alternative energy solutions based on renewable resources is not just an option, but a necessity. In this context, the integration of on-grid Solar Power Plants



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(PLTS) in residential areas can be a strategic step to diversify supply sources, reduce pressure on the main network, and at the same time empower communities in the transition to clean energy (Tarigan, 2020).

Although on-grid PV systems offer significant efficiency opportunities in the context of urban housing, suboptimal design can actually drastically reduce their performance. One of the main challenges is the mismatch between the energy production capacity of solar panels and household electricity consumption patterns that vary across time and seasons. A study by Cubukcu & Gumus (2020) emphasized the importance of simultaneously analyzing electrical loads and solar radiation projections to determine the most efficient panel capacity and orientation. In addition, the integration of energy storage systems (battery storage) that is not properly considered is also a weak point that can cause loss of surplus energy during the day, as well as full dependence on the PLN network at night or when it is cloudy.

On the other hand, the net-metering policy that allows consumers to sell excess energy to PLN does not fully support long-term economic incentives. The revision of regulations that limit the ratio of electricity exports to the grid (for example in ESDM Ministerial Regulation No. 26/2021 which limits exports from 100% to only 65%) makes the economics of on-grid solar power projects less attractive, especially for the lower middle class (IESR, 2023). Without adequate fiscal and technical incentive policies, such as initial installation subsidies, tax breaks, and the availability of green credits, the adoption of on-grid solar power in residential areas will stagnate. Therefore, optimizing solar power plant design not only requires a precise technical approach, but also requires regulatory support and innovative business models in order to become a real solution for the sustainable energy transition in Indonesia's urban environment.

The limited scientific studies on optimizing the design of on-grid solar power plants in urban residential areas show that there is still a gap between academic approaches and practical needs in the field. Many studies only focus on general technical aspects such as panel efficiency or inverter capacity, without considering the complexity of the Indonesian urban environment, such as limited roof space, shadows from high-rise buildings, and fluctuations in electrical loads due to the use of increasingly digital household appliances. In fact, according to Kanata et al (2024), the success of solar power plant adoption is greatly influenced by system design that is contextual to local conditions, including building orientation, micro weather patterns, and household energy consumption habits. Without a design approach based on local data and long-term energy simulations, the implementation of solar power plants will only be a symbolic project, not a sustainable solution.

Furthermore, the weak integration between research results and energy policies at the local government level also slows down the acceleration of on-grid solar power plant utilization. City governments, which should be pioneers in the energy transition, often do not have a clear roadmap for developing renewable energy infrastructure for the residential sector. The lack of collaboration between academics, technology providers, and regulators means that scientifically proven design recommendations are not translated into applicable technical regulations or incentive programs. According to a report by the United Nations Development Programme (UNDP, 2022), the success of residential solar power projects in developing countries is highly dependent on the synergy between local research and responsive policies. Therefore, a case study in Indonesia is urgent, not only to fill the gap in the literature, but to build an integrative model that can be replicated nationally within the framework of the clean energy transition

METHOD

This study uses a qualitative approach with a case study method that aims to explore in depth the design process, implementation, and challenges of optimizing the design of on-grid solar power plants in urban housing areas in Indonesia. The location of the case study was selected purposively, namely in one of the urban housing complexes that have implemented an on-grid solar power plant system, for example Permata Bintaro Housing, South Tangerang or Kota Baru Parahyangan Housing, West Bandung, which have characteristics of dense population, high electricity usage, and access to solar energy technology.

Data were collected through in-depth interviews with various key informants, such as homeowners using solar power plants, housing developers, solar power system providers (installers), local ESDM officials, and academics or energy practitioners. In addition, direct observations were made of solar power plant installations on site, including measurements of panel orientation, roof surface area, integration with the PLN network, and inverter usage and system monitoring. Documentation and document studies (e.g. government regulations, project reports, and technical publications) were also analyzed to understand the regulatory and policy context.

Data analysis was conducted using data reduction techniques, data presentation, and iterative conclusion drawing, using a triangulation approach to ensure the validity of the findings. The focus of the analysis was directed at how the PLTS design was adjusted to the technical and social characteristics of housing, how obstacles emerged in the implementation process, and how optimization strategies could be developed based on best practices in the field. The results of this study are expected to provide conceptual and practical contributions in the planning of on-grid solar energy systems in urban areas in Indonesia.

RESULT AND DISCUSSION

Author Name & Year	Article Title	Research Summary
Umam et al. (2021)	Performance Analysis of 120 kWp GridConnected Rooftop Solar Photovoltaic System in Central Java	Performance analysis of 120 kWp ongrid rooftop solar power system in Central Java: comparing actual and simulated output, and identifying factors causing deviation.
The Greatest Showman (2022)	TechnoEconomic Simulation of Ongrid PV System at a New Grand Mosque in Bukittinggi using HOMER	Technical-economic simulation of ongrid PV system using HOMER for public buildings, provides a method that can be adapted to urban residential scale.
Arifin et al. (2023)	Economic Feasibility Investigation of OnGrid and OffGrid Solar Photovoltaic System Installation in Central Java	A case study in Sragen (Central Java) compares the economic feasibility of ongrid vs offgrid options in housing, with cost, HOMER and LCOE analysis.
Alfiandito et al (2025)	Optimization of Rooftop Solar Power Plant Design at the BAPENDA Building, West Java	Optimization of rooftop PV design by considering orientation, slope, and size, through optimal system efficiency simulation.

Author Name & Year	Article Title	Research Summary
Simanjuntak et al. (2024)	Analysis Of Solar Power Public Street Lighting Optimization With PVSyst Software In a Residential Complex Area	Applying PVSyst to optimize the layout and storage capacity of PV power plants in housing complexes, relevant for ongrid solutions.
Prasetyo et al. (2024)	TechnoEconomic Assessment of Solar Power Plants on River Land in Indonesia Using HOMER Pro	HOMER Pro study of ongrid PLTS in Indonesian river land: Positive NPC, LCOE, and BEP illustrating the feasibility of the technology nationally.
Nurdiana et al. (2020)	Performance analysis and evaluation of a 10.6 kWp ongrid PLTS system et evaluation of a 10.6 kWp on the roof of PUSPIPTEK Serpong: grid-connected photovoltaic performance ratio, capacity, and efficiency system in Serpong	Evaluation of the 10.6 kWp ongrid PLTS system throughout 8 months of monitoring.

Technical Strategy for Optimizing On-Grid Solar Power Plant Design in Urban Environments

The technical strategy for optimizing the design of on-grid Solar Power Plants (PLTS) in urban environments is a complex approach and requires special attention to various technical and spatial factors. Based on studies by (Umam et al., 2021; Alfiandito et al., 2025) it was found that the main challenges in implementing PLTS in urban areas lie in limited space, shadow obstacles from surrounding buildings, and fluctuating electricity load needs throughout the day. In this context, the orientation and tilt aspects of the solar panels are very important, where orientation towards the equator with a tilt angle of around 10 to 15 degrees has been shown to provide optimal solar energy absorption efficiency, especially in tropical areas such as Indonesia. Adjustments to the shape and contour of the existing roof are also crucial so that the system can be installed optimally without disrupting the structure or aesthetics of the building.

In addition, the choice of inverter type has a significant impact on the overall system performance. In densely built-up areas that are prone to shading, the use of micro-inverters has proven to be superior to string inverters, because they are able to manage panel output individually and reduce the impact of performance degradation due to partial shading. To design an efficient system, simulation software such as PVSyst and System Advisor Model (SAM) are essential tools in analyzing energy potential, estimating power losses due to shading, and optimizing system configurations. These simulations also allow for a thorough evaluation of technical variables such as array arrangement, inverter capacity, and daily and seasonal energy production patterns (Utamidewi, 2023).

In its application, the design of on-grid PLTS in urban environments requires a modular and adaptive approach that allows installation on various types of roof surfaces such as concrete roofs, sloping tiles, and canopies. Therefore, the use of lightweight aluminum or galvanized steel frame structures is highly recommended, and in some cases, Building Integrated Photovoltaics (BIPV) technology is even considered for better aesthetic and functional integration (Nugroho, 2020). No less important is the influence of tropical weather typical of Indonesia, high humidity, hot temperatures, and high rainfall, which can accelerate panel degradation if not anticipated through the selection of appropriate protective materials and structural designs that allow for self-cleaning and good drainage.

The need for non-uniform electrical loads, especially with spikes in the morning and evening, must also be responded to with a design strategy that considers oversizing the system capacity so that daytime production can cover energy needs at other times through an energy import-export mechanism with the PLN network. By utilizing a grid-tied inverter that is able to synchronize with the voltage and frequency of the electricity grid, the PLTS system can function efficiently without energy storage batteries (Konde et al., 2022). This overall strategy aims for the on-grid PLTS system to not only produce maximum energy, but also be able to integrate harmoniously with urban infrastructure and operate reliably in various environmental and social conditions. Technical optimization like this makes PLTS not just a complementary technology, but a functional, adaptive, and sustainable clean energy solution in the midst of dense urban areas.

Economic Feasibility and Cost Analysis of Household-Scale Solar Power Plants

The economic feasibility of a household-scale Solar Power Plant (PLTS) system is a very crucial aspect in encouraging the adoption of renewable energy by the wider community, especially on-grid systems that are directly connected to the PLN network. In several recent studies such as those conducted by (Anugrah & Pratama, 2022), an analytical approach using simulation tools such as HOMER Pro has become the main method for evaluating the economic potential of PLTS installations in the household sector. Through this simulation, various key indicators such as initial investment costs, Levelized Cost of Energy (LCOE), and Net Present Cost (NPC) can be projected accurately in a long-term context. The initial investment cost of a household PLTS system, which generally ranges from IDR 20 million to IDR 45 million for a capacity of 1 to 3 kWp, includes the price of solar panels, inverters, supporting systems (Balance of System), installation costs, and operations and maintenance. Although this figure is quite large for many households, the simulation results show that this system still offers economic benefits in the medium to long term.

One of the main indicators of feasibility, namely LCOE, shows that the average cost of electricity production from household solar power plants ranges from IDR 1,200 to IDR 1,800 per kWh, which in many cases is lower than the current non-subsidized PLN electricity tariff (Prasetyo et al., 2024). This shows that technically and economically, solar power plants can be a competitive alternative. Meanwhile, the NPC value, namely the total system cost during the operational period calculated in present value, determines how efficient the system is in the long term. For example, a study by Prasetyo et al. (2024) shows that a 2 kWp solar power plant system has an NPC of around IDR 38 million over a 20-year service life, with potential savings in household electricity bills reaching IDR 3 to 4 million per year. Thus, this system offers a promising return on investment, although it takes between 9 and 12 years to reach the break-even point without incentive support. However, this payback period can be shortened to 6 to 8 years if there is an initial subsidy from the government, making it more attractive to consumers (Arifin et al., 2023).

However, there are several major challenges in implementing household-scale solar power plants. High initial investment costs are a major obstacle, especially for low- to middle-income households. The lack of financing schemes such as green credit, leasing, or pay-as-you-go models also makes this technology less affordable. In addition, the limited incentives from local governments, both in the form of direct subsidies and tax deductions, slow down the adoption of this technology. In fact, various studies show that providing subsidies of up to 30-40% can significantly increase solar power adoption. In an interview with one of the solar power plant users in the Depok area, West Java, Mr. HW stated,

"I installed a 2 kWp solar power plant because my household electricity bill kept going up. After 2 years, I have felt significant savings, and if there is financial assistance, I am sure more of my neighbors will follow suit."

In line with that, Mrs. RN, a PLTS user in Sleman, Yogyakarta, said,

"At first I was hesitant because it was expensive, but after there was a subsidy program from the local government, the installments became lighter. Now I even want to increase the capacity."

These quotes show how the decision to adopt solar power is heavily influenced by adequate incentive and financing support. Scientifically, the findings are supported by the study of Herindrasti et al (2024) in Renewable and Sustainable Energy Reviews, which states that fiscal incentives and supportive financing play an important role in accelerating the penetration of household solar power plants, especially in countries with underdeveloped financial infrastructure. In addition, the International Renewable Energy Agency (IRENA, 2021) noted that countries that adopted a combination of incentive policies, low-interest credit, and educational campaigns succeeded in increasing the number of small-scale solar power plant installations by more than 300% in five years. The existence of subsidy and microcredit programs in several cities in Indonesia played a major role in reducing LCOE locally and accelerating the break-even point to below 7 years. Therefore, in order for the household solar power system to develop more widely, an integrated strategy is needed in the form of expanding fiscal incentives, easy access to microfinance, and net metering regulations that support households to get maximum benefits from the energy they produce. In addition, public education regarding the long-term economic benefits of solar power plants is also the key to success. Overall, these findings suggest that, with proper financial planning and policies, household solar PV systems have bright prospects as a sustainable energy solution that is not only environmentally friendly, but also economical.

Adaptation of Renewable Energy Technology and Policy in Residential Areas

Adaptation of renewable energy technology and policies in residential areas, especially in the context of implementing rooftop solar power plants (PLTS), shows great potential but still faces various challenges. Although PLTS technology is commercially available and has begun to be adopted in several regions, its scale is still limited and its distribution is uneven. National policies such as Presidential Regulation No. 112 of 2022 have provided a clear direction for accelerating the development of renewable energy, but its implementation at the regional level is still not optimal due to the lack of implementing regulations, concrete incentives, and technical capacity. In this context, a community-based approach is very important. Studies (Simanjuntak et al., 2024; Nurdiana et al., 2020) emphasize that direct community involvement in the management and utilization of PLTS will create a sense of ownership and increase the sustainability of the energy system being built. This approach can also avoid the risk of elitism, namely when only the middle to upper economic class can afford to install PLTS due to the high initial investment costs. Without intervention in the form of subsidies, inclusive financing schemes, or cooperative-based partnerships, solar energy can be an exclusive solution that actually widens the gap in energy access in society.

In an interview with one of the managers of an energy cooperative in Yogyakarta, Mr. AS stated,

"We see that the enthusiasm of the residents is quite high, but they are hesitant because the incentives are not yet clear, and most still think that PLTS is expensive and complicated to get permits for."

This quote confirms that there is still a gap between public interest in renewable energy and the readiness of the regulatory ecosystem and available financial support. In this case, collaboration between academics, the private sector, and regulators is needed to develop technical standards, incentive systems, and installation and maintenance guidelines that can be widely implemented. The role of academics is important in providing local technology research and innovation that is more affordable and in accordance with the characteristics of housing in Indonesia. On the other hand, the private sector can be a strategic partner in providing equipment, installation services, and financing, while the government is tasked with creating a supportive policy ecosystem, including improving incentive schemes such as net metering. Unfortunately, the net metering scheme in Indonesia is still considered less attractive since the new policy that only counts 65% of the electricity exported to the PLN network as credit. This reduces public interest in investing in rooftop solar power systems because the return on investment takes longer.

Beyond the technical and policy aspects, challenges also arise in the integration of the PLTS system into the national electricity grid. Many PLN networks, especially in the regions, have not been designed to accommodate the two-way flow of solar energy produced independently by customers (Asminar, 2024). Problems such as voltage stability, limited local network capacity, and the absence of an adaptive grid management system are major obstacles. Therefore, strengthening network infrastructure and digitizing monitoring systems need to be part of a grand strategy for the energy transition. This entire process requires synergy between stakeholders and the courage of local governments to innovate in locally-based energy policies. Without an inclusive and collaborative approach, the great potential of solar energy in residential areas will be difficult to realize as a real solution in the transition to clean and equitable energy.

Recent literature shows that the successful adoption of renewable energy, including rooftop PV, is highly dependent on local policy support and community participation (IRENA, 2023). A study by Fauzi (2023) emphasized the importance of a “just energy transition” that emphasizes social justice in the distribution of benefits from new energy technologies. On the technical side, research by Panjadinata (2024) showed that the main obstacles to PV integration in the residential sector lie in the lack of interoperability between the PV system and the PLN grid, as well as weak technical support from local authorities. Meanwhile, community-based approaches have proven effective in other countries such as Germany and Japan, where the formation of energy cooperatives has been able to reduce initial investment costs and strengthen social support for solar energy projects (Cohen et al., 2021). This suggests that Indonesia can also adopt a similar model by adapting the approach to the local socio-economic context, as long as it is supported by supportive regulations and strong cross-sector collaboration

CONCLUSION

Preventive maintenance is superior to reactive corrective maintenance because it can reduce downtime, extend machine life, and reduce long-term maintenance costs. Although more expensive up front, this approach is more operationally and financially efficient. The use of technologies such as IoT, CMMS, and predictive analytics can optimize preventive maintenance strategies by predicting failures early, reducing downtime by up to 50%. However, the success of preventive maintenance depends on the readiness of digital infrastructure and the competence of human resources (HR) who are skilled in managing the technology. Continuous training and HR development are essential so that technology can be utilized optimally. Overall, preventive maintenance supports operational efficiency, competitiveness, and industry sustainability.

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