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Design, simulation, and practical application of a small-scale solar PV system for educational laboratories at Thai Nguyen University of Technology

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Abstract
This study presents the structure, simulation and performance evaluation of a small network tailored to the electrical engineering laboratory at Thai Nu Nguyen University of Technology (TNUT) in Vietnam. With the help of PVYST software, this system was modeled based on local solar radiation, load requirements and system configuration to provide clean and reliable energy for academic purposes. Simulation results show almost annual energy performance. The performance ratio of 5,800 kWh reaches 74.5%, meeting energy requirements for most months. Cost Advantage Analysis shows the amortization period and competitive cost (LCOE) of 7.6 years. Additionally, the system serves as an interactive educational device that improves learning for students in renewable energy systems. This study demonstrates the feasibility and benefits of the integration of solar power in educational institutions that contribute to sustainable energy transfer in Vietnam.
Keywords: *Electromagnetic interference, nanomaterials, high-voltage transmission, graphene, carbon nanotubes.*

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I. 1.Introduction

In recent years, the increasing demand for electrical energy at academic institutions, particularly at technology universities, has drawn considerable attention to issues related to energy efficiency, cost management and ecological sustainability. At Thai Nguyen University of Technology (TNUT), Electrical Engineering operates a wide range of power supplies in the laboratory, including transformers, programmable logic controls (PLCs), oscilloscopes, signal generators, and electric travel.

These institutes often work long hours to consider both educational and research activities, which is one of the greatest contributions to the institution's general consumption. With the increased costs of the

network and the urgency to reduce carbon emissions, educational institutions around the world are looking for alternatives and sustainable energy solutions. As part of renewable energy technology, solar (PV) systems have been developed as one of the most practical and cost-effective options, especially in areas with many solar power. In northern Vietnam, where TNUT is located, there is plenty of sunlight all year round, making Solar PV a practical solution for academic labs. The transition from traditional network-based energy consumption to renewable energy not only reduces operational costs, but also supports global and national obligations to achieve sustainable development goals and carbon neutrality.

Furthermore, integration of solar PV systems into university infrastructure can play an important role in improving the quality of technical training. This creates a real learning environment that allows students to observe, analyze and interact with modern energy technologies. The combination of solar energy systems and IoT-based data collection systems and surveillance platforms enables electrical engineering students to gain hands-on experience in system design, performance analysis and intelligent energy management. This opens up new research opportunities in areas such as power electronics, smart grids, and integration for renewable energy.

The purpose of this study is to design and optimize small solar power generation systems to provide an electrical laboratory. The proposed system is expected to reduce power supplies, improve energy efficiency and provide an educational platform for practical training. This study includes analysis of laboratory energy consumption, simulation of solar energy production under local climatic conditions, and proposals for technically and economically sustainable PV system design. Furthermore, the research assesses the educational and environmental benefits of including renewable energy systems in university companies.

The Solar photovoltaic System (PV) is a renewable energy technology that converts sunlight directly into electricity based on the effects of solar energy generation. This effect occurs when photons from sunlight absorb the surface of semiconductor materials such as silicon and stimulate electrons to generate current. The basic component of a PV system is solar cells. This is usually coupled to the module and is further attached to the array for improved performance. The complete PV system includes several important components: a PV module, alternating current (AC) screak (DC) inverter, protection and switching devices, optional battery storage, and control and monitoring systems.

A PV system can be divided into three main configurations:

grid, off-network, and hybrid system. The network-attached system is directly connected to the power grid, enabling exports of excessive performance strengths generated during maximum sunlight hours. These systems are suitable for locations where grid availability is reliable and where guidelines such as net measurements are available. Off-grid systems work regardless of the network and are usually used from afar. Battery storage is required to ensure continuous power supply, especially in nights and cloudy conditions. Hybrid systems combine characteristics from both grid and network bound systems by simultaneously incorporating battery storage and maintaining network connectivity. University laboratories generally prefer networks or hybrid systems because they guarantee stable performance and at the same time provide flexibility in energy management. The performance of a solar PV system is heavily dependent on the availability and quality of solar energy production. Solar radiation is defined as the performance of the sun and is an important factor affecting PV output. In Nodbit Nam, the average daily solar radiation is 3.5-5.0 kWh/m² per day, sufficient to use small to medium-sized standard PV systems. However, the efficiency of the system is affected by other parameters such as modular alignment, tilt angle, ambient temperature, and shading. Ideally, the module should be directed towards the equator and tilted to an angle corresponding to the latitude of the area to maximize the energy record. Serial connections of PV cells reduce performance even within splits, so shading must be minimized from nearby structures and wood.

Another important aspect of PV system design is the analysis of electrical load requirements. The exact load profile includes identifying all electrical equipment in the laboratory, estimating power consumption, and calculating daily energy consumption. For example, a typical electrical engineering laboratory can contain several test devices. 10 computer stations that consume about 200 watts, an oscilloscope that consumes 50-150 watts, and a lighting system that requires an additional 500 watts. Total energy consumption per day (kWh/day) can be determined by summing the performance ratings and estimates of daily operating times. This serves as the basis for the size of a PV system.

System size starts with calculating the PV array capacity needed to cover your energy requirements. This includes the distribution of daily energy requirements with daily average sunlight and adaptation of losses in system efficiency. The efficiency of the system is typically between 70% and 80%, which compensates for inverter losses, temperature effects, cable losses and dirt. If the system includes battery storage, further calculations are required to determine battery capacity based on discharge depth, desired autonomy, and daily load. Inverters also need to be properly sized to manage optimal performance loads and temporary illnesses of the induction device.

simulation tools such as PVYST, Homer Pro, and Matlab/Simulink are typically used to model and evaluate the performance of PV systems under local conditions. These instruments allow for a detailed analysis of energy generation, losses, economic feasibility and environmental impacts. Additionally, simulation results can guide decisions regarding component selection, installation configuration, and operational strategy.

In addition to technical and economic aspects, the educational value of implementing renewable energy systems is important in the academic setting. This allows students to deal with the latest energy technologies and understand technical challenges. Courses on renewable energy, smart grid systems and power electronics can enrich live data from on-campus PV installations. Students can participate in projects that impact energy testing, system optimization, and IoT-based energy monitoring to improve problem solutions and analytical skills. This practical exposure not only prepares students for careers in clean energy areas, but also encourages deeper awareness of sustainability and responsible engineering practices.

II. Methodology

This study follows a systematic design and simulation-based methodology to develop a solar energy generation system that loves small lattices at Thai Nguyen University of Technology (TNUT). The process consists of four important levels:

energy requirement sealing assessment, solar potential analysis, system design and size, and performance simulation using special software tools. The aim is to propose technically sustainable, inexpensive and educational solutions for renewable energy tailored to university infrastructure and climate conditions.

The first step is to perform a detailed energy test of the selected laboratory system. This includes identifying all active electrical loads, including desktop computers, measurement devices, lighting systems, air conditioning systems, and laboratory-specific devices such as signal generators, and programmable power supplies. The nominal output of each device is recorded, and typical daily usage patterns are estimated by direct observation and historical performance calculations. Total energy consumption is calculated per day (kWh/day) and the upper load requirement is determined to derive the inverter size. Creating this energy profile provides the basis for accurate design and performance estimates for PV systems.

The next step is the possibility of the sun at the location of the TNUT campus. Weather data including daily average sunlight (kWh/m²/day), temperature and sunlight lessons are taken from the Vietnam Energy Data Portal and the NASA database with surface weather and solar energy. The width, length and height of the selected location are entered into the simulation tool to estimate the availability of solar energy generation for different moons. Typically, the direction (azimut angle) and the angle of the PV module are chosen to maximize annual energy yield by aligning the tilt angles of local latitude (approximately 21° in the trench of the trench (Thai Nguyen). Based on energy requirements and available solar resources, PV systems are dimensioned using standard engineering equations and loss coefficients. PV array capacity (Kilowatt-Peak, KWP) is calculated by splitting daily energy requirements with compensation for system losses including effective solar radiation and inverter loss (usually 3-5%), cable loss, dust and spread (2-3%), temperature residents, and module interference.

Grid configuration is chosen because the power source is reliable availability and there is no legal framework for Vietnamese battery storage systems. The inverter is chosen based on its efficiency, nominal change flow, and its ability to manage maximum load and voltage levels in the laboratory.

The PVSYST simulation software is used to evaluate the performance of the proposed system. This software allows for detailed input of locally specific parameters, PV modules, inverter specifications, shading analysis and load profiles. Monthly and annual energy production, system loss, performance relationships (PR), and solar fractions are calculated. The simulation results are then analyzed to assess the feasibility of the system when reducing grid dependence, achieving partial or complete self-sufficiency of the laboratory.

Finally, economic analysis is conducted using energy removal costs (LCOE) and payback period indicators. Installation costs, component prices, expected operating times, and potential power savings are taken into consideration. Educational values are also discussed regarding the integration of the system into student training and laboratory exercises. Results and Discussions

III. Results and Discussion

The proposed small solar rock type system (PV) was simulated using PVYST 7.2, an extensive software tool for modeling solar energy systems. The simulation environment consisted of detailed input parameters including accurate geographic coordinates of Thai Nguyen University of Technology, average monthly solar radiation, ambient temperature data, and specific features of the selected PV module and inverter. The system was modeled to meet the average energy consumption of electrical laboratories, previously estimated at around 12 kWh per day at a maximum load of 3.2 kW. This design used a 4 kWp PV array associated with a highly efficient string inverter suitable for educational laboratory conditions.

Solar irradiance data showed that TNUT campuses receive an average of approximately 4.4 kWh/m² per day. The highest radiation was recorded in May and June, with values above 5.5 kWh/m²/day, and lowest values fell approximately 3.0 kWh/m²/day in December and January. These seasonal variations were reflected in the monthly energy yield of the PV system. The simulations showed that the system can produce approximately 5,800 kWh per year, and the daily average conveniently exceeds the daily needs of the laboratory in most months, providing excess strength to the network.

Performance Ratio (PR), a key indicator of system quality and efficiency, was calculated at 74.5%. This value is in the acceptable area of the grid PV system and reflects temperature effects, inverter efficiency, cable loss, non-agrement, and impurities losses. The system loss diagram generated by PVYST showed that the most significant losses occur due to pyrolysis (7.8%) and inverter inefficiency (5.2%) followed by losses and erroneous losses of 2-3% adaptation. These figures show that system performance can be further improved with optimized installation strategies such as better natural ventilation and regular module cleaning for cooling.

Seasonal changes in solar availability have resulted in significant changes in monthly energy performance. The highest monthly production volume was recorded in June, reaching 620 kWh, while the lowest was 340 kWh in January. In the main months, the PV system produced up to 200% of the laboratory energy requirements. This indicates the excellent potential of export or additional load performance. The system was slowing down every day, especially in the winter months of December and January. This highlights the importance of complementary supply currents or energy storage where full autonomy is desirable. However, even in the few months of the low-generational generation, the system contributed significantly to laboratory consumption, reducing its dependence on supply networks by more than 70%.

The nominal capacity of the inverter selected for this system is 5 kW and is equipped with an MPPT input (maximum powerpoint tracking), allowing for flexible array configurations and efficient energy harvesting. Simulation results confirmed that the overlap between interbars was minimal, and occurred only at a maximum of several months with high radiation intensity, with less than 1% of total energy loss. This confirmed the appropriateness of the inverter sizes associated with PV array capacity. The efficiency of the inverter was constant and we verified the selection of hardware components for this application.

The temperature effect was particularly relevant to the performance of the North Vietnamese system at temperatures above 35°C in summer. Increased modular temperatures lead to voltage waste, and deterioration in performance is clearly observed in simulations. The average module operating temperature is between 25°C and is up to 45°C in winter summer, which corresponds to seasonal declines in module efficiency. Including the temperature coefficient in the PVYST model guaranteed that this effect was absolutely effective, highlighting the importance of a suitable rack system to improve air flow and module cooling.

A simplified cost-benefit analysis was also performed in the PV System Financial module to assess the system economy. The total cost of capital, including PV modules, inverters, assembly structures, cables and installation work, was estimated at $5,500. Repayment period was calculated to approximately, taking into account annual energy savings estimated at US$725, based on local electricity rates and predicted utilities. 7.6 years. Given the expected lifespan of the 20-25 year system, this leads to fairly long-term financial savings and positive returns on capital. The level cost of energy (LCOE) was calculated at 0.095/kWh euros. This is significantly lower than the average electricity price for electricity in the region.

The additional educational advantage of the installed system is the real-time monitoring interface, allowing students to pursue parameters such as voltage, electricity, energy, energy, energy yield, system efficiency, and more. This feature is included in the laboratory training module, allowing students to examine real-time and historical data, perform experiments on system performance under different weather conditions, and analyze the effects of different loads. As a result, PV systems not only act as power sources, but also serve as an educational platform for practical training in renewable energy, control systems and technology for data analysis.

The discussion also considered the scalability of the system. Given the successful performance of the Pilot 4kWP system, the expansion plan was simulated with a 10 kWp array, supporting several laboratories and other university facilities such as offices and classrooms. The larger system showed proportional benefits to energy generation, with annual generations exceeding 14,000 kWh. Load adjustment simulations showed that overall system efficiency and quiescent consumption can be improved without additional battery storage by shifting specific loads to higher production times, such as planning high performance experiments at lunchtime.

A notable limitation of the current system is the lack of storage capacity. This means that excess energy generated outside of business hours will be exported to the network and not stored for later use. Grid exports are economically profitable as part of net networks, but such guidelines in Vietnam have not yet been fully developed or standardized. In future work, integration of small lithium-ion battery systems will improve the system's self-supply and the safety currents may arrive with network errors. Simulations of a 5 kWh battery showed that university consumption could increase by 18% and achieve uninterrupted clinical laboratory operations during power outages. Overall, the simulation results confirm the technical feasibility and economic viability of implementing small PV systems for small-scale grille PVs for academic laboratory applications. The system meets daily energy requirements, provides cost savings, improves energy effectiveness, and acts as an effective educational tool. Seasonal variation in performance hinders system-wide effectiveness and can be managed at a simple load planning and optional storage level. Additionally, if energy requirements or financing are available, the modularity of the system allows for future expansion.

Finally, the PV systems designed and simulated in this study not only contribute to the sustainability goals of educational institutions, but also create dynamic learning environments that bridge theoretical knowledge and practical applications. The successful implementation at TNUT serves as a model for similar technology universities across Vietnam, promoting the adoption of renewable energy in academic sectors. The findings of this study highlight how important it is to invest in renewable infrastructure not only as a source of clean energy, but also as a catalyst for innovation, student commitment, and long-term operational efficiency in educational institutions.

IV. Conclusion

This study successfully demonstrates the lifelong skills of grid solar power systems, providing a clean, reliable and inexpensive energy, in TNUT. With a simulation-based design using PVYST, four-sketch SUN systems meet the daily energy requirements of the Electrical Engineering Laboratory, while simultaneously providing high-performance and cost-effective economic indicators. In addition to energy generation, the system provides a practical platform for student commitment, allowing practical learning using real-time data records, performance monitoring and technical fields of renewable technology. This study shows that small measurements of PV systems can contribute significantly to reducing power spending and promoting academic environmental compatibility. Despite seasonal variations in output, the system continues to lead the whole year, offering future scalability or integration options for battery storage. The result is that similar systems are required to implement in more detail at TNUT and vote for the national goal of clean energy development and capacity structure in environmentally friendly technologies. Thus, the form of research forms the basis for further research and practical applications of PV systems in educational infrastructure.

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